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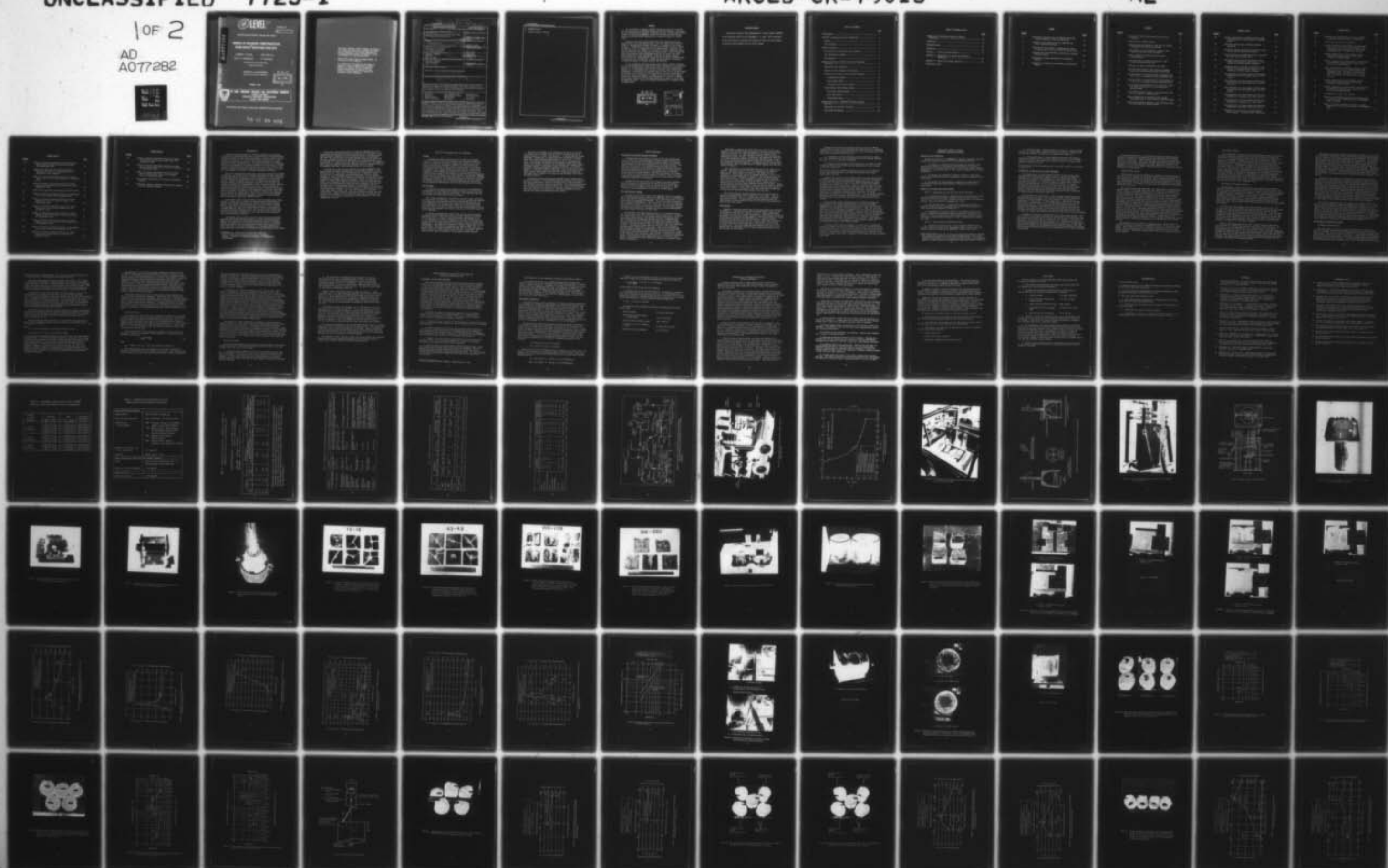

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REMOVAL OF EXPLOSIVES FROM PROJECTILES USING CAVIJET® CAVITATING FLUID JETS

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18. SUPPLEMENTARY NOTES This project was accomplished as part of the US Army's Manufacturing Methods and Technology Program. The primary objective of this program is to develop, on a timely basis, manufacturing processes, techniques, and equipment for use in production of Army materiel.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Explosives	Load, Assemble, Pack	MMT-Ammunition
Ammunition	Army Ammunition Plants	Fluid jet cutting
Demilitarization	Manufacturing	Jet cutting
Energy conservation	Reclamation	Cavitation

20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The feasibility of using a CAVIJET cavitating fluid jet to remove high explosives from munitions has been examined. In tests with specimens of TNT and Composition B, no detonations occurred despite exposure at pressures well above anticipated operational values. From laboratory studies with an inert explosive simulant, the conceptual design for a pilot CAVIJET explosive removal facility has been established. These studies suggest that use of cavitating jets will provide an efficient new method for cleaning projectiles, using less energy than thermal techniques which employ steam or hot water and operating at less than one-half the pressure of the high-

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20. ABSTRACT Cont'd:

pressure washout technique.

SUMMARY

The feasibility of using a CAVIJET cavitating fluid jet to remove TNT and Composition B from rejected projectiles was examined. The scope of work included safety testing, laboratory testing to determine optimized system and operating parameters, energy and economic analyses against competing demilitarization systems and a conceptual design of a pilot plant.

Removing explosives from projectiles with a cavitating jet was demonstrated to be safe and efficient. Over 200 safety tests were performed at operating and overtest pressures. No reaction of any kind occurred. Probabilities of safety at the 95% confidence level of 95.2% for TNT and 97.4% for Composition B were demonstrated. Operating and system parameters were varied in an attempt to optimize material removal rate and material removal rate per unit energy input. Nozzle design and operating parameters were established which can be used as the first trial during pilot plant evaluation. Economic and energy analyses indicate that the cavitating jet system has the potential of both energy and operating cost savings over current explosive removal techniques. A conceptual design of a pilot facility was prepared.

It is recommended that the existing high pressure washout facility at Iowa AAP be modified to allow a full scale evaluation of the effectiveness of the CAVIJET method on HE loaded 155 mm and 8-inch projectiles. Further, it is recommended that the pilot facility study includes the development of cavitating jet cutting heads for both the 155 mm and 8-inch projectiles, evaluation of a filtering system to allow recirculation of the process water, evaluation of a means to control the foaming which occurs with the present system, and installation of a dryer to reduce the moisture content of the reclaimed explosive to enable it to be sold to commercial users. Action is currently being taken to implement these recommendations.

ACKNOWLEDGEMENTS

During the course of this investigation, we were deeply saddened by the untimely death of our colleague, S. L. Rudy. His creativity, which contributed to virtually all aspects of this and every program in which he participated, will be sorely missed.

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INTRODUCTION

Currently employed methods for removing explosive from rejected projectiles at Army Ammunition Plants or projectiles to be demilitarized at Depots include such techniques as steamout, hot water washout (ref 1), direct melt and rinse (ref 2) and high pressure washout (refs 3 and 4). Depending on quantity and quality, the reclaimed explosive is either burned or sold to commercial users. Growing prohibition of open burning and other environmentally unacceptable methods for disposing of rejected explosive necessitates the use of special furnaces (refs 5 and 6). The explosive removal methods using steam require copious amounts of energy. This has motivated a search for improved alternative techniques.

The use of high pressure water jets, operating typically at 68.9 MPa (10,000 psi), has proved to be a feasible alternative to melt techniques offering substantial reductions in energy consumption for the removal of high explosives such as Composition A-3, Composition B, or TNT (refs 3 and 4). However, attendant with the use of these high pressures are problems related to system maintenance, specifically in the need for frequent replacement of pump packings, seals, and nozzles due to erosion caused by the high exit velocities of the jets. Also, although the existing system at the Iowa Army Ammunition Plant (IAAP) has proved capable of removing the majority of the Composition B explosive from 155mm projectile, M549's, occasionally trace amounts adhere to the metal and must be removed by a steam rinse. Thus, it is felt that this existing system will not be capable of production cleaning of larger warheads such as the 8-inch projectile, XM650E5 (ref 7).

A new method, which uses cavitation erosion to augment the cutting action of a fluid jet, is capable of removing missile propellants at pressures well below those currently used by a high pressure washout system. The CAVIJET[1] cavitating fluid jet process was used to remove the propellant and liner from TARTAR missile motors at a pressure of 17.9 MPa (2600 psi), which was almost half of the 34.5 MPa (5,000 psi) required by the non-cavitating jets. The CAVIJET process removal rate was one-third faster; consequently, only one-third of the energy per motor was needed (refs 8 and 9).

The promise shown by these successful field trials with CAVIJET suggested that similar energy savings, at reduced operating pressures, might also be achieved in demilitarizing explosive-filled munitions. However, questions about the relative differences between the energies required to ignite or detonate propellants versus those required for high explosives, as well as differences in the erosion properties of these substances, motivated the feasibility study described in this report.

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1 US Patent Nos. 3,528,704; 3,713,699; and 3,807,632.
Other US and Foreign patents are pending or have been granted. CAVIJET is a registered trademark of HYDRONAUTICS, Incorporated.

One primary concern with regard to using the CAVIJET process for eroding and removing explosives was the potential for detonation by the highly energetic implosion of the cavitation bubbles. Stresses greater than 689.4 MPa (100,000 psi) have been estimated for this mechanism (ref 10), although it should be emphasized that these stress pulses are of extremely brief duration (on the order of a few micro-seconds), and operate over very small areas (less than 0.02 mm (0.001 in.) in diameter). Thus, answering questions about the inherent safety of exposing explosives to cavitation was one of the prime objectives of this program.

Of relevance to this safety question is a study performed at the Royal Armament Research and Development Establishment (RARDE) in Great Britain (ref 11). This study was motivated by a comparable concern for the safe use of conventional, non-cavitating water jets for cutting explosives. Thus, the RARDE scientists established a device which, in a single shot, caused a jet of water to be driven by a propellant against samples of various RDX explosive compounds. It was not until they produced a jet traveling at 1600 m/s (5,250 ft/s) that one detonation was achieved; although initiations which failed to propagate were observed in other tests. The stagnation pressure corresponding to this jet velocity is over 1,280 MPa (186,000 psi), and the impact pressure (using the "water-hammer" equation: $p = \rho c v$, where ρ is the density of water; c the sound speed in water; and v the jet velocity) is 2,340 MPa (339,500 psi). These extremely high stress estimates provide some indication of how difficult it is to detonate this type of explosive with ordinary or cavitating jets operating at nozzle pressures of 68.9 MPa (10,000 psi) or less.

CAVIJET® CAVITATING FLUID JET TECHNOLOGY

Concept

A CAVIJET cavitating fluid jet is one of the few successful attempts to harness, for useful purposes, the destructive power of cavitation, which has for decades plagued the designers of certain types of hydrodynamic equipment. The basic concept consists of stimulating the growth of vapor-filled cavities within a relatively low velocity liquid jet by appropriate nozzle design. With proper adjustment of the distance between the nozzle and the surface to be fragmented, these cavities are permitted to grow from the point of formation then collapse on that surface in the high pressure stagnation region where the jet impacts the solid material. Because the collapse energy is concentrated over many small areas, extremely high, localized stresses are produced. This local amplification of pressure provides the CAVIJET cavitating fluid jet with an advantage over any steady non-cavitating jet operating at the same pump pressure and flow rate.

Test Facility

An experimental facility was designed and built at HYDRONAUTICS, Incorporated, for studying and developing practical devices which use the CAVIJET cavitating fluid jet principles. The components used for this program are shown schematically in Figure 1.

The primary components of the facility include a pump, reservoirs to recover and store the water, filters, controls, pressure and temperature gauges and flow measuring devices for accurately measuring all system parameters, and a large test chamber which contains the means for translation of the CAVIJET nozzle relative to test specimens at precisely controlled rates of motion and at any desired angle of attack. Within this test chamber, tests may be conducted on specimens either in air or submerged.

A portable quintaplex pump (fig 2) was used for both the safety evaluations and the laboratory trials with inert explosive simulants. This pump provides a range of flow and pressure combinations up to 5.7 L/s (90 gpm) at 17.3 MPa (2,500 psi) or 68.9 MPa (10,000 psi) at 1.3 L/s (20 gpm), by the use of replaceable fluid ends, or plunger and packing kits. The power envelope for the pump is shown in fig 3, with indications of the application possible at several combinations of flow and pressure. This pump is manufactured by American Aero, Inc., of Houston, Texas, and has their Model No. WBD-190V. It has five plungers and is driven by a diesel engine, rated for 142 kW (190 BHP). The engine and the pump are mounted on a four-wheeled tandem trailer.

The main test chamber in the laboratory (fig 4) is 1.5 m wide, 1.8 m long, and 1.2 m deep (5 ft by 6 ft by 4 ft deep) and has a working capacity of 2,840 L (750 gallons). It can be used for either stationary, translating, or manual operation of CAVIJET cavitating water jets, which have been extended by 5.1 cm (2 in.) or 1.9 cm (0.75 in.) flexible high-pressure hoses for any of these modes of usage. This chamber is fitted with a removable wooden cover which retains the splash to facilitate in-air testing, and contains lights to permit viewing or photography during the testing. A hydraulic system for controlling nozzle translation is also a part of the test chamber. A hydraulic cylinder, gear pump, sump, and four-way control valve complete this system, which provides translation velocities from less than 2.5 cm/sec (1 in./sec) to over 90 cm/sec (36 in./sec) in either direction.

A schematic showing some typical CAVIJET nozzle configurations is given in figure 5. The centerbody design is usually more effective for in-air applications, while the turning vane is often preferable for submerged cutting or drilling situations. For certain applications such as propellant and explosive removal, the "plain" CAVIJET nozzle, i.e., the CAVIJET nozzle body without inserts, is capable of providing sufficient intensity of cavitation. This plain CAVIJET nozzle was used for the tests conducted during this program.

SAFETY EVALUATION

Motivation for Safety Evaluation Testing

Although water jet pressures as high as 68.9 MPa (10,000 psi) (refs 3 and 4) have been used before to remove explosives from projectiles, safety tests were deemed necessary because of the unique characteristics of the erosion provided by the CAVIJET process. The highly erosive nature of the CAVIJET process is caused by local impulsive stresses of an extremely brief duration which may be over an order-of-magnitude larger than the average pump pressure which is driving the CAVIJET nozzle flow. This distribution of localized severe stresses provides CAVIJET's improved performance over conventional jets, but also provides a matter of concern. Thus, tests were conducted on specimens of actual explosives to provide data to allow a hazards analysis to be performed.

Details of this test series and the hazards analysis performed with the results are contained in the report provided by Hazards Research Corporation (HRC), which sub-contracted this work. Their report (ref 12) is presented in its entirety in Appendix A. The following section supplements information in the HRC report.

The Experimental Program

The plan for the safety tests of the CAVIJET process was created after consultations among personnel from ARRADCOM, HRC, and HYDRONAUTICS. All of the explosive specimens as well as the 105mm projectiles used in these tests were provided by ARRADCOM. The test equipment components were provided by HYDRONAUTICS. The tests were run at the HRC explosive test facilities where 0.3 m (12 in.) thick concrete walls were imposed between the test stand and operating personnel. HRC personnel handled the explosives exclusively throughout the testing, while HYDRONAUTICS personnel operated the pump and test stand.

The portable, quintaplex American Aero, Inc., pump described in the previous section of this report was used in these tests. A special test stand (figs 6 and 7), with specimen holders designed for rapid turn around during testing, was designed and built by HYDRONAUTICS after discussions with ARRADCOM and HRC explosives handling experts. The test stand has a 110 L (29 gal.) container which allowed erosion testing of the CAVIJET process while the specimens were fully submerged in water. Controlled out-flow from near the top of the container insured complete submersion at all times. This fully submerged test mode simulates the mode of cutting which is anticipated for CAVIJET nozzles while operating in actual explosive filled projectiles. A few in-air tests were also performed. The duration of the tests on blocks of TNT and Comp B was controlled remotely with a pneumatically activated device. Test durations, which ranged from 0.2 s to over 30 s, were varied in conjunction with the operating pressures, as detailed in the tables in Appendix A.

The holder to support the 10 by 10 by 2.5 cm (4 by 4 by 1 in.) explosive block allowed rigid positioning of the block during erosion testing and insured that large stresses were not imposed on the explosive surfaces. For this reason all surfaces that contacted the explosive were made of nylon. In addition, any adjustments which had to be made during the testing utilized nylon threaded studs so that in case an explosive particle became trapped in the threads it would not experience excessive stresses. The assembly of the circular base, holder-support, and a specimen holder is shown (removed from the test stand) in figure 8.

Two orientations of the specimens were used in the safety evaluations. The first, known as the "top orientation", is shown in place in the holder support in figure 8. The holder for this orientation, which allows the jet to impinge upon the 2.5 cm (1 in.) thickness, is shown separately in figure 9. The second position, the "edge orientation", is shown in figure 10, with an eroded specimen block still in place. This orientation caused the jet to erode upon the 10 cm (4 in.) thickness, in order to allow a longer time of exposure before the jet eroded completely through the specimen. Three of the removable specimen holders of each type were provided to expedite the testing sequence. Thus, while one holder held the next specimen ready to be tested, a second was in the test stand being eroded, and a third held the specimen being measured after the test.

The entire specimen support assembly could be removed from the circular aluminum holder in the bottom of the test stand. After removing this assembly (fig 11), a 105mm shell could then be inserted into the test stand. In this manner, the same stand was used for small blocks of test explosive as well as the actual 105mm projectiles used in full scale tests.

Test Results

Complete details and tabulations of the test results are contained in Appendix A. Typical blocks of TNT and Composition B tested in the top orientation are shown in figures 12 and 13. Similar photographs of explosives tested in the edge orientation are shown figures 14 and 15. Depending on the pressure and the length of time the specimen was exposed to the energy provided by the CAVIJET nozzle, a typical specimen initially experienced erosive material removal, frequently followed by a fracturing of the specimen into two or more pieces. This pattern of erosion followed by fracturing was a reproducible feature of many of these tests. The tests exhibiting this behavior were used in comparison with the subsequent tests of inert materials described in the next section of this report.

Throughout the 230 tests performed with test blocks of TNT and Composition B and the 11 tests performed on 105mm projectiles containing Composition B, no explosive events occurred. The conclusions drawn from this safety evaluation by HRC are that:

1. Composition B testing yielded a 97.4% probability of safety at a 95% confidence level for the CAVIJET process in removing explosive at a pump pressure of 20.7 MPa (3,000 psi).

2. Testing of TNT yielded a 95.2% probability of safety at a 95% confidence level for the CAVIJET process operating at a pump pressure of 20.7 MPa (3,000 psi).

HRC concluded that the CAVIJET cavitating fluid jet process "appears to be a very effective device for removing explosive from 105mm projectiles" (ref 12).

Although the results of the hazards analysis of these tests yielded probabilities of safety which are slightly below the 98.5% probability at a 95% confidence level recommended by ARMCOM Regulation No. 385-4, 21 March 1975, it should be kept in mind that no reactions occurred throughout this safety test series. Thus, it is anticipated that the probabilities of safety which were calculated would be higher if a somewhat more extensive test series had been conducted. For this reason, the HRC report recommends conducting 200 tests with loaded projectiles, since this is the necessary sample size to establish the 98.5% probability of safety at a 95% confidence level. It was decided, however, because no reactions occurred, that sufficient safety evaluations had been performed to satisfy the objectives of the first phase of this program.

More extensive safety evaluations will be performed during the second phase of the program which involves a complete full-scale examination of the CAVIJET cutting head as well as shell rotation and feeding of the cutting head into the projectiles. Since the full-scale simulation of the operational configuration was not included in the test plan for Phase I, testing was deferred. Also, it should be emphasized that tests were safely performed with the CAVIJET process, under pressures up to 68.9 MPa (10,000 psi) well beyond the 20.7 to 34.5 MPa (3,000 to 5,000 psi) anticipated for production use of a CAVIJET cutting head. Safe operation at 68.9 MPa, coupled with the extremely strong dependence of the intensity of a cavitating jet on pump pressure, combine to accentuate the safety of the CAVIJET process.

Although the HRC report concluded that there was no significant difference between the erosion characteristics of TNT and Composition B, further examination of the test results indicated that Composition B was more difficult to erode. Subsequent analyses have been concentrated on removal of Composition B, with the understanding that comparable, if not more rapid, removal rates could be expected for TNT under the same operating conditions.

LABORATORY TESTING TO DEFINE SYSTEM AND OPERATING PARAMETERS

Laboratory Test Objectives

Testing was conducted at HYDRONAUTICS' CAVIJET cavitating fluid jet testing and evaluation facility with the following objectives:

1. To examine the effects of various system and operating parameters on the ability of the CAVIJET cavitating fluid jet process; specifically on the volume removal rate[2], $\dot{V}$, and volume removal effectiveness,[2] e_v, in simulated tests of the removal of explosives from 105mm projectiles.

2. To develop the information required to design a pilot plant which uses the CAVIJET process for production removal of explosives from projectiles.

3. To provide the data required to compare the effectiveness of the CAVIJET process with other methods of removing explosives from projectiles.

Summary of the Laboratory Test Program

Part 1: Calibration of Sand and Inert Filler Specimens

1. Configuration studies - conducted with as-received inert filler. Established that the as-received filler could not be used, and that 10 x 10 x 2.5 cm (4 x 4 x 1 in.) specimens could be used for calibration purposes (fig 8 and Appendix B, tables B-1a, B-1b).

2. Sand content effect - varied sand content from 0 to 60% to establish erosion behavior comparable to that of TNT and Composition B (figs 19 and 20 and Appendix B, table B-2).

3. Orientation and pressure effects - by comparing results from tests on Composition B and inert filler with 60% sand, derived scale factor: f = 1.5 as multiplier for volume removal and effectiveness data from inert testing (figs 19 through 27, table 3 and Appendix B, tables B-3, B-4).

Part 2: Volume Removal Effectiveness Study

1. Preliminary rotating tests - using existing CAVIJET nozzles, examined effects of nozzle size, impingement angle, rotation rate, and pressure (figs 28 through 35 and Appendix B, tables B-5a, B-5b).

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2 The volume removal rate, $\dot{V}$, may be either directly measured or inferred from weight-loss measurements by using specimen density. The volume removal effectiveness, e_v, is given by $e_v = \dot{V}/P$, where P is the hydraulic power for a given nozzle at the particular operating pressure (table 1).

2. Pilot hole tests - using preliminary designs for leading CAVIJET nozzles, in cutting head, examined effects of orientation, rotation rate and pressure (figures 36 through 42 and Appendix B, table B-6).

3. Cutting head tests - using cylindrical specimens with precast simulated fuze holes and with a cover plate having 5 cm (2 in.) diameter opening to represent fuze opening in projectile (figs 43 through 53 and Appendix B tables B-7a,b,c).

Further details of the test plan and all of the test results are contained in Appendix B.

Calibration of Sand and Inert Filler Specimens

The original plan for this program included erosion studies with a standard inert filler material which is used to simulate the weight of explosives, such as TNT and Composition B, in various munitions for ballistic test purposes. The properties of this inert filler E (Type II) are listed in table 2. As discussed below, the initial tests with this material established that, in the as-received condition, it was not suitable for our purpose. Thus, it was found necessary to modify the as-received filler by adding a percentage of sand. The addition of 60% sand by weight provided a test material which simulated the erosion behavior of TNT and Composition B observed during the safety evaluations at Hazards Research Corporation (table 2).

The procedure for casting various test specimen configurations was developed by trial and error. The casting technique finally established required mixing and preheating the inert filler and sand mixture at a temperature of 99°C (210°F) for about eight hours. The mixture was then precooled to a temperature of 77°C (170°F) before being poured into the mold (fig 16 and 17). This precooling was established as necessary to minimize the shrinkage of the material after being poured into the mold. Because of the high viscosity of the inert filler and sand mixture, considerable stirring and agitation of the mix was required within the mold to remove air pockets and establish a smooth uniform surface for the specimens.

Specimens in different configurations were used in these studies. The first, 10 cm (4 in.) cubes, were used for studies which established that the as-received inert filler was not suitable for this program. The second configuration, a 10 by 10 by 2.5 cm (4 by 4 by 1 in.) block, was the same as that used in the tests on TNT and Composition B. Although this configuration was initially planned for use during safety evaluations, only, it was also found to be suitable for the comparative tests which established the scaling factor between the erosion behavior of the explosives and the inert filler/60% sand mixture.

For the rotating tests, a cylindrical specimen was designed which partially simulated the configuration of the explosive filler actually loaded in a projectile. These cylinders were 10 cm (4 in.) in diameter and 10 cm (4 in.) long. Both solid cylinders and cylinders with an opening cast in one surface to simulate the fuze hole in an explosive load were used. To cast the simulated fuze hole, which was 5 cm (2 in.) in diameter by 7.6 xm (3 in.) deep, a plug was inserted in the molten specimen during the cooling process.

Configuration Studies

First series of tests was designed to establish a suitable configuration for the test specimen, to learn the required steps for casting the inert material to simulate the explosive, and to understand whether or not the erosion behavior of the inert filler material was suitable for simulating, in laboratory trials, the behavior of an actual explosive such as TNT and Composition B. The results of these tests are summarized in Appendix B, tables B-1a and B-1b.

Two types of tests were performed. The first involved translating the CAVIJET nozzle in a straight line across the surface of the specimen at various constant velocities ranging from 1.3 to 30 cm/s (0.5 to 12 in./s). In this translating test mode, a CAVIJET nozzle with an orifice diameter of 3.2 mm (0.125 in.) and nozzle pressure of 10.3 to 15.2 MPa (1500 to 2200 psi) were used. The standoff distance (the distance between the nozzle and the surface being eroded) was 3.8 cm (1.5 in.). As seen in Appendix B, table B-1a, this as-received inert filler exhibited erratic erosion behavior. The photographs in figure 18 are typical of these preliminary test results. At sufficiently low translating speeds and/or sufficiently high pressures, threshold fracturing occurred. No reproducible pattern of erosion could be achieved in these tests. Apparently the fractures initiated at weak points in the grain structure of the cast material or in a flaw pattern which emerged during the cooling process. This fracture behavior, with minimal erosive cutting, was different from the erosion response of the TNT and Composition B specimens tested during the safety evaluations. Consequently, it was established that as-received material could not be used in simulation studies of the system and operational parameters for a CAVIJET explosive removal facility.

The solution to this problem, as suggested by Mr. George Petino, Jr., of Hazards Research Corporation, involved the addition of sand to the inert filler. Since Composition B had a multiphase structure, it was felt that adding a granular phase (sand) to the simulant would produce the desired erosion behavior. Subsequent testing proved this to be a workable solution to the problem.

Sand Content Effect

The testing used to examine whether the addition of sand would provide the desired explosive simulation is contained in Appendix B, table B-2. The specimen configuration for these tests was 10 by 10 by 2.5 cm (4 by 4 by 1 in.). Specimens containing 0, 40, 50, and 60 percent of sand by weight were examined. Two CAVIJET nozzles were used for these tests. The first had an orifice diameter of 3.2 mm (0.125 in.) and the second was 2.2 mm (0.086 in.). The pressure range for these tests was from 10.3 to 68.9 MPa (1,500 to 10,000 psi). Standoffs for these nozzles were 3.8 and 2.2 cm (1.5 and 0.88 in.), respectively. As with all subsequent tests, these erosion studies were performed with both the specimen and the CAVIJET nozzles submerged. This mode was used because it is anticipated during the actual removal of explosives. Examination of the erosion behavior of the specimens revealed that the mixture containing 60% sand by weight provided the best simulation of the explosive behavior. This was anticipated to be the best mixture, since Comp B is approximately 60% granular material. This mixture was used in all subsequent tests.

Orientation and Pressure Effects

The preliminary tests described above also revealed that the inert filler/sand mixture was more difficult to erode than the actual explosives. That is, higher energy inputs were needed to remove a given volume of material in comparison to the explosive when exposed to the same CAVIJET nozzle under identical conditions of testing. It was evident that to quantitatively extrapolate the results of these tests to select design parameters for a pilot explosive removal plant, a "scale factor" would have to be derived. This scale factor would be used to predict Composition B volume removal rates and volume removal effectiveness based on tests with the inert filler/60% sand mixture.

To derive this scale factor, tests were performed using 10 by 10 by 2.5 cm (4 by 4 by 1 in.) specimens having the same geometry as the explosives, but cast from the 60% sand and inert filler E mixture. Typical erosion responses of these specimens are seen in figures 19 and 20. As in the tests on the actual explosives, both the "top" and the "edge" were used. The edge orientation tests, although not totally satisfactory because of breakout of the jet due to the thinner specimen cross section in this orientation, were necessary to give greater distance over which the eroding action could be observed, particularly at the higher pressures.

Tests to derive the scale factor were conducted with the same plain, 2.2 mm (0.086 in.) CAVIJET nozzle used in the tests on the explosives. All tests were run in the submerged mode at a standoff of 2.2 cm (0.88 in.). The pressures used were 20.7, 31.0, and 41.4 MPa (3,000, 4,500, and 6,000 psi). Although the pressures used on the explosive ranged up to 68.9 MPa (10,000 psi), results from tests at this pressure were inconclusive because the 68.9 MPa jet was capable of cutting completely through the specimen during the briefest exposure. The three pressures cited above, provided a sufficient range to establish the behavior of the inert material.

The results from these tests are summarized in figures 21, 22, and 23. A characteristic dependence is found for the volume removal effectiveness, e_v, as a function of the time of exposure of the material to the cavitation erosion created by the CAVIJET cavitating fluid jet nozzle. The typical rise, peaking, and roll-off of these curves is observed for all erosion situations of this type (refs 13 and 14). To compare these results from the inert material with those for the explosives, a comparison with one specific aspect of this non-linear time relationship was made. The peak of these curves was selected as a suitable point of comparison. These peak volume removal effectiveness values, along with those for Composition B, are summarized in table 3. The curves from which the peak volume removal effectivenesses for Composition B were obtained are shown in figures 24, 25 and 26.

As indicated in figures 21 through 26, as well as in the raw data tabulations for these materials in Appendix B, tables B-3 and B-4, various erosion and fracture modes were observed for both the explosive and inert materials. In many tests, before a well established erosion pattern could be established, catastrophic fracture of the material occurred. In these cases, fragments of the specimen were frequently lost and hence an accurate estimation of the eroded volume removed from the material by the action of cavitation could not be made. Such test results were excluded from the sets of data used to derive the scale factor. Again it was observed that Composition B was more resistant to erosion by cavitation than was TNT. For this reason the comparisons made here are limited to the more difficult to erode Composition B. Hence, these results provide a conservative estimate of the ability of the CAVIJET process to remove TNT from projectiles.

The results listed in table 3 are summarized in figure 27 where the peak e_v values are plotted versus the pressure used in each test. On this log-log plot, characteristic power law dependences on pressure for the CAVIJET cavitating fluid jet are observed (ref 14). To derive the scale factor, f, ratios were taken at various values on each of the straight lines which had been faired through the two data sets in figure 27. Averaging these ratios provided a value for the scale factor of: $f = 1.5$. This factor is the necessary multiplier which was used in later analyses to extrapolate the results with the inert filler/sand material to predict the potential of the CAVIJET for the removal of explosives from projectiles.

Volume Removal Effectiveness Study

Preliminary Rotating Tests

The second part of the test program (see Appendix B) examined the influence of system and operating parameters such as nozzle size and type, rate of translation of the jet upon the surface to be eroded, rotation rates, and pressures. The objective was to maximize volume removal effectiveness, which is a measure of efficiency. The results of these tests are summarized in Appendix B, tables B-5a and B-5b. All of these tests were performed on inert solid right-circular cylinders 10 cm (4 in.) in diameter and 10 cm long.

Two CAVIJET nozzle sizes were used. The first had an orifice diameter of 3.2 mm (0.125 in.), and the second was 3.6 mm (0.140 in.).

The test configuration is shown in figures 28a and 28b. The specimen is constrained in a removable holder (fig 28c). The holder is mounted on a rotatable shaft (fig 28b). A variable speed drive capable of a continuous range of rotation rates up to 156 rpm was used to rotate the specimens. The CAVIJET nozzles were oriented at the desired line of attack and angle and then hydraulically translated towards the specimen at a preselected rate.

To reduce the size of the test matrix for these tests, a single rate of translation, or "feed", was selected. The rate chosen, 8.4 mm/s (0.33 in./s) was influenced by the rates reported for the IAAP facility (ref 4), i.e., an average cycle time of 2 min. 26 s to traverse up and back the 45.7 cm (18 in.) length of the 155 mm projectile. This corresponds to an average feed rate of about 6.3 mm/s (0.25 in./s). The rate chosen for the rotating tests is about 34% faster than the average IAAP feed rate. This implies that the CAVIJET process may clean projectiles in a proportionally shorter time than conventional high pressure washout.

The actual relative velocity of the jet across the surface being eroded is the vector addition of the two velocity components provided by the linear translation of the CAVIJET nozzle and the rotating velocity of the specimen. Some of the erosion patterns achieved during these preliminary tests are seen in figures 29 and 30.

The data defining these tests were: the operating pressures and flow rates which established the input hydraulic power, P, in accordance with the equation: $P = kpQ$ (1)

where

$k = 1$, for the pressure, p, in MPa and flow, Q, in L/s

($k = 5.834 \times 10^{-4}$, for p in psi and Q in gpm);

and the weight of the specimen before and after the test. Using the density of the material, 1.94 g/cm^3, the volume removed was calculated. Then, using the known time of exposure of the jet upon the surface of the material, the volume removal rate, $\dot{V}$, was calculated. Volume removal rate versus the nozzle pressure for tests with a 3.2 mm (0.125 in.) CAVIJET nozzle is plotted in figure 31. Volume removal effectiveness e_v, for the 3.2 mm nozzle is plotted in figure 32. Some typical test specimens which were eroded by a 3.6 mm (0.140 in.) CAVIJET nozzle are shown in figure 33. Comparable results for this 3.6 mm (0.140 in.) CAVIJET nozzle are presented in figures 34 and 35.

The difference in the erosion results obtained for these two sizes of CAVIJET nozzles may be seen by comparing the curves in figures 31, 32, 34, and 35. The relative dependence of $\dot{V}$ on pressure is somewhat steeper for the larger nozzle (compare figures 31 and 34). This effect of a greater sensitivity between volume removal rate and pressure for larger nozzle diameters is consistent with results obtained with CAVIJET on other materials (refs 14 and 15). Examining volume removal effectiveness, there is a decrease in e_V with increases in pressure for the 3.2 mm (0.125 in.) CAVIJET nozzle while the reverse is true for the larger CAVIJET nozzle (figs 32 and 35). CAVIJET nozzle sizes that provide an optimum tradeoff between volume removal effectiveness and use of available hydraulic power will be selected for the pilot plant.

Also shown in figures 34 and 35 is the effect of the rotation rate on the erosion of these inert cylinders. The 20 rpm tests provided more effective volume removal than did similar tests at 40 rpm. A second variable, the flow path leading into the CAVIJET nozzle, may have been the overriding factor leading to the results seen here. A fixture supporting the nozzle which caused a 45° bend in the flow prior to entering the nozzle was used for the 40 rpm tests. This rerouting of the flow could have decreased the nozzle effectiveness by introducing excessive swirl and/or turbulence to the jet.

Pilot Hole Tests

The objective of these tests was to examine the ability of the leading CAVIJET nozzle to cut into a rotating specimen and create the initial hole in the explosive into which the cutting head could penetrate. The configuration for these pilot hole tests is shown schematically in figure 36. Typical results for these tests, which were conducted with a 3.2 mm (0.125 in.) CAVIJET nozzle orientated at $\theta = 30°$, are shown in figure 37. These tests were run at 27.6 and 34.5 MPa (4,000 and 5,000 psi) nozzle pressure, with 40 and 80 rpm rotation rates.

These results were plotted against the relative velocity of the jet against the surface of the sample. This velocity, v, is derived with the following relationship:

$$v = \sqrt{v_T + v_N}, \qquad (2)$$

where

$v_N = \pi DN/60$, and: v_T, D, and N are defined in figure 36.

The volume removal rate as a function of the relative translation velocity is summarized by the data plotted in figure 38. The volume removal effectiveness derived from these volume removal rates is shown in figure 39.

All data obtained for this section of the test plan are summarized in Appendix B, table B-6. For this configuration of the pilot hole CAVIJET nozzle, effectiveness is fairly insensitive to the relative velocity over a range of from about 1,000 to 1,900 cm/min. (400 to 750 in./min.), indicating that, effective volume removal rates can be achieved within a range of 40 to 80 rpm. Also, the results (figs 38 and 39) show that over the pressure range of 27.6 to 34.5 MPa (4,000 to 5,000 psi), $\dot{V}$ and e_V are relatively unchanged.

A comparable test series was conducted with a nozzle with a 45° angle of impingement. Typical appearances of specimens tested with a 3.2 mm (0.125 in.) CAVIJET nozzle oriented at 45° are shown in figure 40. These specimens were tested over a range of pressures from 20.7 to 34.5 MPa (3,000 to 5,000 psi) and at rotation rates of 20, 40, and 80 rpm. The volume removal rate and the volume removal effectiveness are plotted as a function of the relative velocity of the jet to the surface of the material being eroded in figures 41 and 42. An optimum $\dot{V}$ and e_V for this configuration occurs at about 1,000 cm/min. (400 in./min.) which corresponds to a rotational rate of 40 rpm. The effect of pressure is greater with the 45° nozzle, i.e., tests conducted at 34.5 MPa (5,000 psi) show higher values of $\dot{V}$ and e_V. The 30° nozzle at 40 rpm, is slightly more effective at 27.6 MPa (4,000 psi) (fig 39). The conclusions are that the 30° impingement provides more effective removal rates and volume removal effectivenesses than the 45° orientation and that 40 rpm rotational rate is optimum for full surface removal of the specimen. These results will be considered in the design of the preliminary CAVIJET cutting head.

The objective of this testing was to establish a nozzle design for merely drilling out a pilot hole through which the cutting head could enter. The results were not as expected. Indeed the CAVIJET nozzles removed material over the entire 10 cm (4 in.) diameter of the test specimens. This testing mode may not have provided a satisfactory simulation of the condition, which would be encountered in the removal of explosives from a 105mm, 155 mm, or 8 in. projectile. The results suggest that if a CAVIJET nozzle could be allowed full access to the surface of the explosive, this single nozzle could achieve removal out to the complete 10 cm (4 in.) diameter of a projectile such as the 105 mm.

Cutting Head Tests

The tests outlined below were conducted to examine CAVIJET effectiveness in removing explosive from projectiles with precast fuze holes. Two test configurations were used in this series:

1. A right circular cylinder, 10 cm (4 in.) in diameter, 10 cm long, with a cylindrical hole cast in one end of the specimen to simulate a projectile fuze hole. The hole was 7.6 cm (3 in.) deep and 5 cm (2 in.) in diameter. In these tests, the pilot hole CAVIJET nozzle was allowed to impinge within the precast fuze hole so that removal of the wall of the hole could be observed.

2. The second test configuration used specimens of the type described above as well as cylinders without a hole. In each case, the surface of the specimen was shielded with a metal plate having a circular opening 5 cm (2 in.) in diameter. This cover plate prevented impingement of the jet on the surface of the specimen, limiting the erosion to the interior of the fuze hole. The data for these tests are summarized in Appendix B, table B-7.

Typical results from these tests are shown in figure 43. These tests were run at 34.5 MPa (5,000 psi) pressure and at both 40 and 80 rpm rotational rates. The same two CAVIJET nozzles used for the pilot hole study, i.e., those having 30° and 45° angles of impingement were used. The results for the 30° tests are summarized in figures 44 through 48. The comparable data for the 45° tests are shown in figures 49 through 53. These results are also tabulated in Appendix B, tables B-7a, B-7b, and B-7c.

The effects of operating parameters on the enlargement of the precast fuze hole were found (figs 44,49). The optimum parameters for this enlargement are: 34.5 MPa (5,000 psi) pressure, 30° impingement angle, and a 120 rpm rotational rate. These specimens experienced both surface erosion of the fuze hole and erosion and breakout of the base of the specimen. Results derived from fuze hole erosion are presented in figures 45 and 47 for the 30° impingement tests, and in figures 50 and 52 for 45° impingements. The total weight loss results shown in figures 46, 48, 51, and 53 are based on fuze hole plus base erosion and breakout.

The relative performance of the 45° impinging CAVIJET nozzle is somewhat better than the 30° orientation for fuze hole erosion only. The results are comparable if base erosion and breakout are included. Optimum performance of the 45° nozzle occurs at about 80 rpm and at 120 rpm for the 30° design. Most effective removal occurs in either orientation at 34.5 MPa (5,000 psi) pressure for the 3.2 mm (0.125 in.) CAVIJET nozzle.

The results of these laboratory tests were used to define the conceptual design and preliminary operating parameters for the CAVIJET explosive removal pilot facility described in the following section.

DESIGN CONCEPTS FOR A CAVIJET® CAVITATING JET EXPLOSIVE REMOVAL FACILITY

Components for the Pilot Facility

The design concepts discussed in this section are based on modification of an existing high pressure water jet washout facility located at the Iowa Army Ammunition Plant[3] (ref 4). This facility, developed to remove high explosives from 155 mm projectiles, was designed to operate at 68.9 MPa (10,000 psi) with a flow capacity of 1.39 L/s (22 gpm). A Tritan Hydro-Laser pump, Model No. 51020SS, driven by a 112 kW (150 hp) explosion-proof electric motor, provides the pressurized water for the system. A hydraulically actuated device is used to translate the cleaning head into the projectile. An air motor rotates the projectile at about 130 rpm during the cleaning. A mechanical device loads projectiles onto the cleanout fixture. The effluent (water with Composition B explosive) is routed through a Rotostrainer which removes solids larger than 250 microns, then pumped to settling tanks in an adjacent carbon filter plant. In the existing facility, there are no means for either recirculating and reusing the water or for drying the explosive for resale purposes.

A schematic drawing of the proposed components for the CAVIJET explosive removal facility is shown in figure 54. As summarized in table 4, this facility will use many of the existing IAAP components. New or modified components are planned to provide:

1. Flow at the rate of about 3.47 L/s (55 gpm) at 27.6 MPa (4,000 psi), which is required for the three-nozzle CAVIJET cavitating fluid jet cleaning head (fig 55).

2. Means to maintain water within the projectile during the cleanout process, causing the explosives and cleaning head to be submerged. This will enhance the erosive action of the CAVIJET nozzles, and minimize air entrapment in the effluent, reducing the possibility for foam formation which has plagued the operation of the existing IAAP facility.

3. Drying of the explosive particles removed from the projectiles, so that the H.E. is in a condition suitable for resale to commercial processors or for possible reuse in other munitions.

4. Recirculation of the water used to clean the projectiles, so that the burden on the existing carbon filter plant is minimized. This will require filtration to remove particles larger than 50 microns and to minimize wear and explosive buildup within the main pump. The heat imparted to the water during passage through the main pump will be removed by a cooling tower.

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3 IAAP is operated by Mason & Hanger - Silas Mason Co., Inc.

Specifications for the components required are provided in table 4.

The preliminary design for a CAVIJET cleaning head, suitable for removal of Composition B or comparable high explosives from M549 155 mm warheads is shown in figure 55. Designed to fit into the fuze opening of these projectiles, the cleaning head must have a coordination of angles α and θ_i, and nozzle orifice diameters so that the overall thrust from these nozzles will be balanced. Otherwise, when the lance is fully extended into the projectile, deflection of the cleaning head may occur. For instance, the thrust from a single, 3.2 mm (0.125 in.) CAVIJET nozzle is about 290 N (66 lb.) at 27.6 MPa (4,000 psi).

Operational Parameters

From the laboratory tests performed on the inert, cylindrical specimens, it is possible to estimate the performance of a three-nozzle CAVIJET cleaning head (fig 55) in removing Composition B from 155 mm warhead M549. The existing IAAP high pressure washout facility requires 2.43 minutes to washout a 155 mm warhead (ref 3). Using the mass of 7.26 kg (16 lb) of Composition B in the 155 mm warhead, and a density of 1.70 g/cm^3 (106 lb/ft^3), one can derive a volume removal rate of 0.10 m^3/hr (3.7 ft^3/hr). Operating with 1.39 L/s (22 gpm) at 68.9 MPa (10,000 psi), this high pressure washout facility delivers a hydraulic power of 96 kW (128 hp). Thus, the volume removal effectiveness for this existing IAAP facility in cleaning Composition B from 155 mm warheads is 1.1 x 10^{-3}m^3/kW-hr (2.9 x 10^{-2}ft^3/hp-hr).

To compare these operational parameters with the potential performance of a CAVIJET cleaning head, consider the volume removal rates achieved at a pressure of 27.6 MPa (4,000 psi) shown in figures 38, 41, 46 and 51. These tests, performed with various specimens and nozzle orientations, used a single 3.2 mm (0.125 in.) CAVIJET nozzle, and produced volume removal rates ranging from about 0.034 to 0.085 m^3/hr (1.2 to 3 ft^3/hr). Using the lowest rate, the scaling factor: f = 1.5, to relate the inert material results to those anticipated for Composition B, and multiplying by three to account for the three nozzles specified in the preliminary cleaning head design, we can estimate:

$$\dot{V} = (0.041)\ (1.5)\ (3) = 0.15\ m^3/hr$$

$$(\dot{V} = (1.2)\ (1.5)\ (3) = 5.4\ ft^3/hr).$$

These 3.2 mm (0.125 in.) CAVIJET nozzles, operated at 27.6 MPa (4,000 psi) (table 1) will deliver a total hydraulic power of 94 kW (126 hp). Thus, our estimated value for volume removal effectiveness for the three nozzle CAVIJET cleaning head is:

$$e_v = (0.15\ m^3/hr \div (96\ kW) = 1.5 \times 10^{-3} m^3/hp\text{-}hr$$

$$(e_v = 5.4\ ft^3/hr \div 126\ hp = 4.3 \times 10^{-2} ft^3/hp\text{-}hr.$$

Relative to the 2.43 minutes now needed to clean the 155 mm warhead these data suggest that the CAVIJET cleaning head could do the job in:

$$t = \frac{0.10 \ m^3/hr}{0.15 \ m^3/hr} \ (2.43 \text{ min.}) = 1.62 \text{ minutes}$$

or two-thirds of the present rate of cleaning.

A cleaning time for the 155 mm warhead of 1.62 minutes is equivalent to a translation rate of 9.4 mm/s (0.37 in./s). The translation rate used in the laboratory tests with inert material was 8.8 mm/s (0.33 in./s). Subsequent estimates of CAVIJET energy and cost requirements use a conservative three-fourths of the high pressure washout cutting time:

$$t = \frac{3}{4} \times 2.43 \text{ min} = 1.82 \text{ min}$$

In summation, the preliminary operational specifications for this facility are:

Nozzle pressure	27.6 MPa (4,000 psi)
Total flow (for three-nozzle cleaning head)	3.4 L/s (54 gpm)
Total delivered hydraulic power	94kw (126 hp)
Translation rate for cleaning head	9.4 mm/s (0.37 in./s)
Rotation rate for projectile	40 to 120 rpm

COMPARISONS OF ALTERNATIVE EXPLOSIVE REMOVAL TECHNIQUES

Current technology used to remove explosive from rejected or unserviceable projectiles varies from plant to plant, but is generally marked by the use of large quantities of steam to melt the explosive from the projectile.

The standard technique used at depots employs the APE 1300 Hot Water Washout and Reclamation System. In this system, projectiles are mounted nose down on a rack. Hot water at about 88°C (190°F) and 0.62 MPa (90 psig) is sprayed directly on the filler which is removed by a combination of melting and erosion. It takes from 30 to 60 minutes, depending on the size of the item, for a medium caliber shell to be cleaned out. The explosive-water slurry is separated, the water is recycled, and the explosive is either flaked or pelletized. The APE 1300 washout process requires multiple processing steps and a variety of equipment for handling fluid, slurries and solids. The process resembles the final steps of the TNT manufacturing process for washing, drying and granulation. The product quality for reclaimed explosives obtained by the washout process is low because of contamination with water, traces of dissolved salts which originate from the water supply, process equipment corrosion products and particles of the projectile liner coating. Pelletized products from the APE 1300 system contain no more than 4% moisture, typically 1 to 2% (refs 1 and 16).

Another technique, used mainly for TNT removal, is steamout. Here a tube connected to a controlled pressure steam line is brought into contact with the exposed explosive. As the explosive melts, the molten explosive, together with the condensed steam, drains by gravity from the cavity. Steamout is effective on cast explosives such as TNT which can be melted with low pressure steam. Composition B cannot be effectively removed from projectiles by the steamout method because of its large percentage of non-meltable RDX.

A third technique, called meltout, has been used effectively to remove explosive from 90 mm and 155 mm projectiles at Ravenna AAP and from 105 mm projectiles at Kansas AAP. At these AAP's, projectiles are placed nose down in a steam cabinet. Low pressure steam, introduced to the cabinet, contacts the exterior of the projectile. As soon as it melts, the explosive is drained into a pan below. Typically, the explosive core remains solid and drops out as a "carrot". The melted explosive is air cooled, broken into chunks and sold to commercial processors. Kansas AAP reports a 30-minute melt time for Composition B loaded 105 mm projectiles. An alternative is to mount the projectiles in the steam cabinet nose up, melt the entire cavity, and then drain the contents. This is done to maintain adequate heat transfer, i.e., air pockets, formed by the drained explosive, retard further effective heat transfer. Iowa AAP employs a

variation of the nose-up meltout technique. They, additionally, introduce direct 34 kPa (5 psig) steam into the noze cavity to speed meltout. A subsequent processing step required with meltout systems is a rinse of steam or hot water. This operation is required to remove any residue of explosive that may remain after meltout, hence the use of the term "melt/rinse" in this report. Kansas AAP performs a 2-minute hot water rinse after meltout of the 105 mm M1 projectile.

All three of the above processes, i.e, hot water washout, steamout, melt/rinse, require significant quantities of steam to melt the explosive and long cycle times, i.e., 30 to 60 minutes. Additionally, they are not suitable for removal of cross linked explosives. The Army is investigating basic improvements to Composition B which, it is expected, will make the resulting product unsuitable for thermal demilitarization techniques.

In an effort to develop a method which could produce large savings in both energy and cycle time, the Iowa AAP established a facility to remove explosive from rejected projectiles using a high pressure water jet. In this system, shells are rotated at about 200 rpm. A 69 MPa (10,000 psi) static jet of water erodes and fractures the explosive. The procedure is performed on one projectile at a time, similar to a drilling operation. Iowa AAP has processed about 19,000 155 mm projectiles on this equipment. Several limitations of this system were discovered during the operational run:

1) Large amounts of thick foam were created which was difficult to handle and dispose of. Foaming was a most severe problem which required several men to shovel out the thick foam from tanks to disposal.

2) Cutting effectiveness was sensitive to how well the nozzles were machined. For example, a burr in the nozzle would significantly reduce its cutting effectiveness.

3) Frequent nozzle replacement was required. Nozzles were replaced once a week on a one-shift basis.

4) High pump maintenance downtime can be expected. Although not a problem with the new installation at Iowa AAP, a 20% pump maintenance downtime is not unusual in a 69 MPa (10,000 psi) high pressure operation.

5) Incomplete washout was experienced. Despite the fact that the system maximum pressure of 69 MPa was used, some 155 mm projectiles required a second pass for thorough cleaning. Washout of 8-inch projectiles would probably require two passes with different nozzles, perhaps a drill pass and a wall wash pass.

6) A large burden was placed on the carbon column water treatment facility. The washout system when operating, generated 1.39 L/s (22 gpm). The capacity of the entire water treatment system is 2.53 L/s (40 gpm).

7) The reclaimed explosive was unsaleable. The screened explosive was burned and not sold to commercial processors. Drying the water-wet explosive would make it a saleable product with a value of about \$0.50 per lb for Composition B and \$0.30 per lb for TNT.

In summary, methods of removing explosive from rejected projectiles include hot water washout, steamout, melt/rinse and high-pressure water washout. Since steamout is not suitable for Composition B fills, economic comparisons are made for the three methods listed and the CAVIJET method.

Appendix C, Energy and Economic Analysis, contains estimates of the energy requirements and operating costs associated with four alternative methods of removing Composition B from rejected projectiles. Table 5 summarizes the comparative energy requirements. The CAVIJET and the high-pressure washout methods, even when a significant amount of energy is added to dry the wet explosive, require less than one-half the energy per projectile when compared to the two thermal methods. Table 6 compares the operating costs of these four methods of explosive removal.

To summarize, the CAVIJET system as conceived appears to offer:

a. 64% potential savings in energy over the hot water washout method and a 60% potential saving in energy over the melt/rinse method.

b. 27% potential cost savings over the high pressure washout method and 28% potential cost savings over the melt-rinse method.

c. Versatility to remove TNT and Composition B as well as possible future cross-linked explosives.

d. Rapid cycle time.

e. Minimal pink water disposal.

f. Explosive reclamation for resale or reuse.

CONCLUSIONS

From the results of the work performed during this program, the following conclusions are drawn:

1. The CAVIJET cavitating fluid jet method can safely remove TNT and Composition B from rejected projectiles.

2. Preliminary operational specifications for Composition B removal from the 155 mm M549 projectiles are as follows:

a.	Nozzle pressure:	27.6 MPa (4,000 psi)
b.	Total flow (for three-nozzle cleaning head):	3.4 L/s (54 gpm)
c.	Total delivered hydraulic power:	94kW (126hp)
d.	Translation rate for cleaning head:	9.4 mm/s (0.37 in./s)
e.	Rotation rate for projectile:	40 to 120 rpm

3. Savings in energy and operating costs can be anticipated if the CAVIJET method is used in lieu of existing demilitarization techniques. For example, a 60% potential savings in energy consumption is projected for a CAVIJET system over a melt/rinse system.

4. In comparison to the high pressure washout method, the CAVIJET method should provide faster and more efficient explosive removal, while operating at less than one-half of the usual 68.9 MPa (10,000 psi) pressure used by the conventional jets. In addition to savings of energy and overall operating costs, the reduced CAVIJET cavitating jet system pressures provide an inherently safer plant, with reduced capital costs for the lower pressure components and increased system reliability. A 27% potential savings in operating costs is projected for a CAVIJET system over the high pressure washout method.

5. The most cost effective means of conducting pilot plant studies of the CAVIJET system is to retrofit the high pressure washout facility located at Iowa AAP.

RECOMMENDATIONS

It is recommended that:

1. Further evaluation of the CAVIJET cavitating jet method be conducted on full scale, HE loaded projectiles.

2. A pilot facility be established at Iowa AAP by modifying the high pressure water washout facility located there.

3. The pilot plant study should include:

a. The development of cavitating jet cutting heads for both the 155 mm M549 and 8-inch XM650 projectiles.

b. Evaluation of a filtering system to allow for recirculation of the process water.

c. Evaluation of a means to control foaming.

d. Installation of a dryer to reduce the moisture content of the reclaimed explosive to enable it to be sold to commercial users.

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18. Correspondence regarding VECP KS-0245-114, Incorporation of Explosive Reclaiming Equipment on 105 mm Line, 20 Dec 76 to 12 Dec 78.

19. Private communication: phone conversation with A. Parkinson, Tooele AD on 17 May 79.

20. Private communication: phone conversation with Mr. Amerson, COR, Ravenna AAP on 23 May 79.

21. Private communication: phone conversation with L. Grignon, Iowa AAP, May 77 to May 79.

Table 1. Performance specifications for CAVIJET® cavitating fluid jet nozzles: plain configuration

Nozzle Orifice Diameter	Pressure		Flow		Hydraulic Horsepower	
	MPa	ksi	1/s	gpm	kw	hp
2.2 mm (0.086 in.)	20.7	3.0	0.51	8.1	10.6	14.2
	31.0	4.5	0.63	10.0	19.6	26.3
	41.4	6.0	0.73	11.6	30.3	40.6
	68.9	10.0	0.96	15.2	66.1	88.7
3.2 mm (0.125 in.)	20.7	3.0	0.98	15.5	20.2	27.1
	27.6	4.0	1.13	17.9	31.3	42.0
	34.5	5.0	1.25	19.8	43.0	57.7
3.6 mm (0.140 in.)	20.7	3.0	1.27	20.2	26.4	35.4
	27.6	4.0	1.48	23.4	40.7	54.6
	34.5	5.0	1.65	26.2	57.0	76.4

Table 2. Composition and properties of the simulated and actual explosive materials

As-received Inert Filler	
Nomenclature:	Inert Filler E (Type II)
Military Specification:	MIL-I-60350(MU), 30 October 1965
Composition: (% by weight)	35% - Glyceryl ester of 12-hydroxy stearic acid (MIL-G-48246) 5% - Rosin, Type I (lump) Grade FF (unrefined dark-colored wood rosin)(LLL-R-626c) 50% - Gypsum, dead burned (MIL-G-48344) 10% - Ferric oxide, Type II (natural, dry red)(MIL-I-706A)
Density (as recast into test specimens):	1.85 gm/cm^3
Hardness:	Shure Type D: 36
Inert Filler with 60% sand (by weight) Mixture	
Sand:	White silica; Penn-Sand, mfr. by Pennsylvania Glass Sand Corp.
Density (of cast mixture)	1.94 gm/cm^3
Composition B	
Density (as cast)	1.70 gm/cm^3

Table 3. Derivation of scale factor: Comparison of tests on Composition B and inert filler/60 percent sand

CAVIJET® NOZZLE SIZE: 2.2-mm (0.086-in.) orifice diameter, plain configuration

TEST MODE: submerged, stationary

SPECIMENS: 10 x 10 x 2.5 cm (4 x 4 x 1 in.)

Pressure		Composition B			Inert Filler/60% sand		
		Time at Peak, s	Volume Removal Effectiveness (Peak)[a]		Time at Peak, s	Volume Removal Effectiveness (Peak)[a]	
MPa	ksi		$10^{-3} m^3$/kw-hr	$10^{-2} ft^3$/hp-hr		$10^{-3} m^3$/kw-hr	$10^{-2} ft^3$/hp-hr
20.7	3.0	3.0	1.90	5.0	0.57	1.04	2.74
31.0	4.5	-	-	-	0.33	1.72	4.54
41.4	6.0	0.30	4.75	12.5	0.44	3.57	9.39
68.9	10.0	0.31	8.47	22.3	-	-	-

[a]These peak values of volume removal effectiveness were derived by averaging only the normal erosion plus fracture data at the peak of each curve in Figures 21 through 26. The peak values are plotted in Figure 27. The scale factor: f=1.5 is the average of ratios taken for e_v values on each of the lines faired through the data in Figure 27.

Table 4. Components for pilot CAVIJET® cavitating jet explosive removal facility

Function	Component	In Existing IAAP Facility	Planned for Pilot CAVIJET Facility
Provide high pressure water to cleaning head	Main pump: Tritan Hydro-Laser, Model No. 51020SS	Fluid end and components for operation at 68.9 MPa (10,000 psi) and 1.39 l/s (22 gpm)	Modified fluid end and components for existing pump, to provide 27.6 MPa (4,000 psi) and 3.47 l/s (55 gpm)
Drive for main pump	Electric Motor	112 kw (150 hp), explosion proof, 3 phase, 60 cycles, 460v	Same
Feed high pressure water from main pump to cleaning head	Flexible hose and rigid lance	12.7mm (0.5in.) I.D., for existing lower flow requirements	25.4 mm (1.0 in.) I.D., for planned flow of 3.47 l/s (55 gpm)
Flooding inside of projectile during cleaning	Trap in discharge duct	Not present	Upward U-bend, to trap water within projectile
Removal of small H.E. particles from water	Strainer	Rotostrainer, removes particles larger than 250 microns	A rotary strainer, with 3.8 l/s (60 gpm) capacity, to remove particles larger than 50 microns
Cooling of recirculating water	Heat exchanger and cooling tower	Not present	112 kw (150 hp) cooling capacity; heat exchanger: about 0.5 m dia. by 3.0 m long (1.5 by 10 ft.); cooling tower: 0.9 by 1.4 m, 2.1 m high (3 by 4.5 by 7 ft.)
Reservoir for recirculating water	Storage tank	Not present	Fiberglass circular tank with washout capability; 1890 l (500 gal) capacity; about 1.2 m dia. by 1.7 m high (4 by 5.5 ft.)
Drying of explosive particles	Dewatering screen, dryer, scrubber	Not present	Capacity: about 2220 N/hr (500 lb/hr), with a vibrating screen; hot air drying, using existing steam source; wet scrubber to remove particles from air flow prior to exhaust
Recirculation of water	Pumps	Sandpiper pump	Capacity: 3.8 l/s (60 gpm), about 0.75 kw (1 hp), two required

Table 5 - Comparison of energy requirements for explosive removal

Item	Hot Water Washout and Recovery		Melt and Rinse		High Pressure Washout and Explosive Drying		Cavitating Jet Washout and Explosive Drying	
	155 mm	8-inch	155 mm	8-inch	155 mm	8-inch	155 mm	8-inch
Steam								
joules (BTU)	67.4×10^6 (63.8×10^3)	109.6×10^6 (103.7×10^3)	68.5×10^6 (64.9×10^3)	107.7×10^6 (102.4×10^3)	16.9×10^6 (16.0×10^3)	27.4×10^6 (26.0×10^3)	16.9×10^6 (16.0×10^3)	27.4×10^6 (26.0×10^3)
Electricity								
joules (kWh)	7.7×10^6 (2.13)	12.5×10^6 (3.46)	- -	- -	14.0×10^6 (3.87)	22.7×10^6 (6.28)	10.3×10^6 (2.85)	16.7×10^6 (4.64)
Unit Energy Req't								
joules	75.1×10^6	122.1×10^6	68.5×10^6	107.7×10^6	30.9×10^6	49.1×10^6	27.2×10^6	44.1×10^6
Annual Energy Req't								
joules	3.00×10^{12}	0.659×10^{12}	2.73×10^{12}	0.582×10^{12}	1.23×10^{12}	0.265×10^{12}	1.09×10^{12}	0.238×10^{12}

Table 6 - Comparison of operating cost estimates for explosive removal

Item	Hot Water Washout and Recovery		Melt and Rinse		High Pressure Washout and Explosive Drying		Cavitating Jet Washout and Explosive Drying	
	155 mm	8-inch	155 mm	8-inch	155 mm	8-inch	155 mm	8-inch
Steam	$0.29	$0.47	$0.29	$0.46	$0.07	$0.12	$0.07	$0.12
Electricity	0.12	0.19	-	-	0.21	0.35	0.16	0.26
Water and Water Treatment	0.02	0.04	0.09	0.14	0.24	0.39	0.01	0.02
Labor	4.40	7.15	3.79	6.17	3.31	5.94	2.58	4.75
Extra Maintenance	-	-	-	-	0.22	0.40	0.09	0.16
Nozzle Replacement	-	-	-	-	0.01	0.02	0.03	0.04
Unit Cost	$4.83	$7.85	$4.17	$6.77	$4.06	$7.22	$2.94	$5.35
Annual Cost	$193,000	$42,000	$166,000	$37,000	$162,000	$39,000	$117,000	$29,000

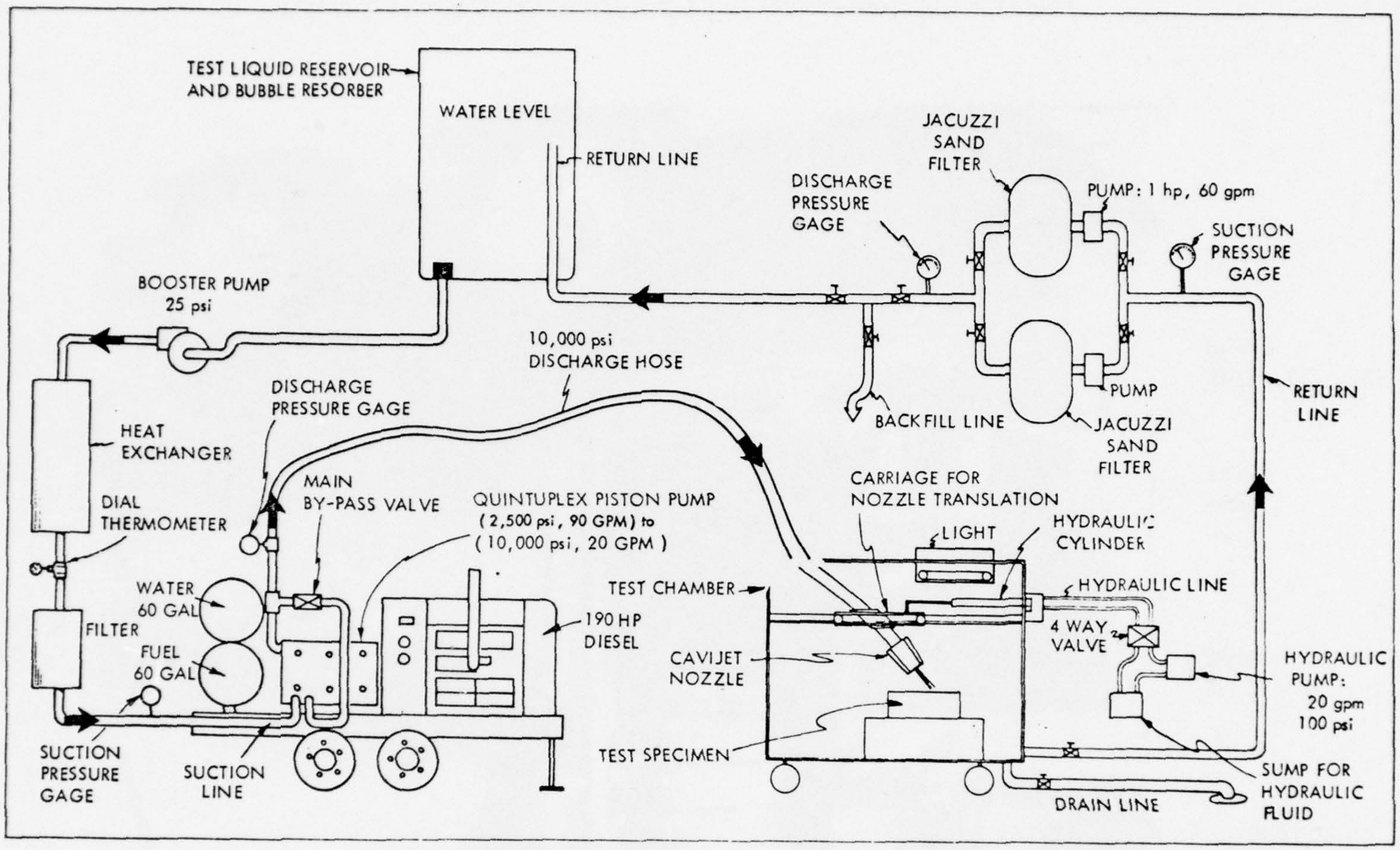


Figure 1 - Schematic of CAVIJET® cavitating fluid jet test facility: indicating modifications to provide 68.9 MPa (10,000 psi) operation.

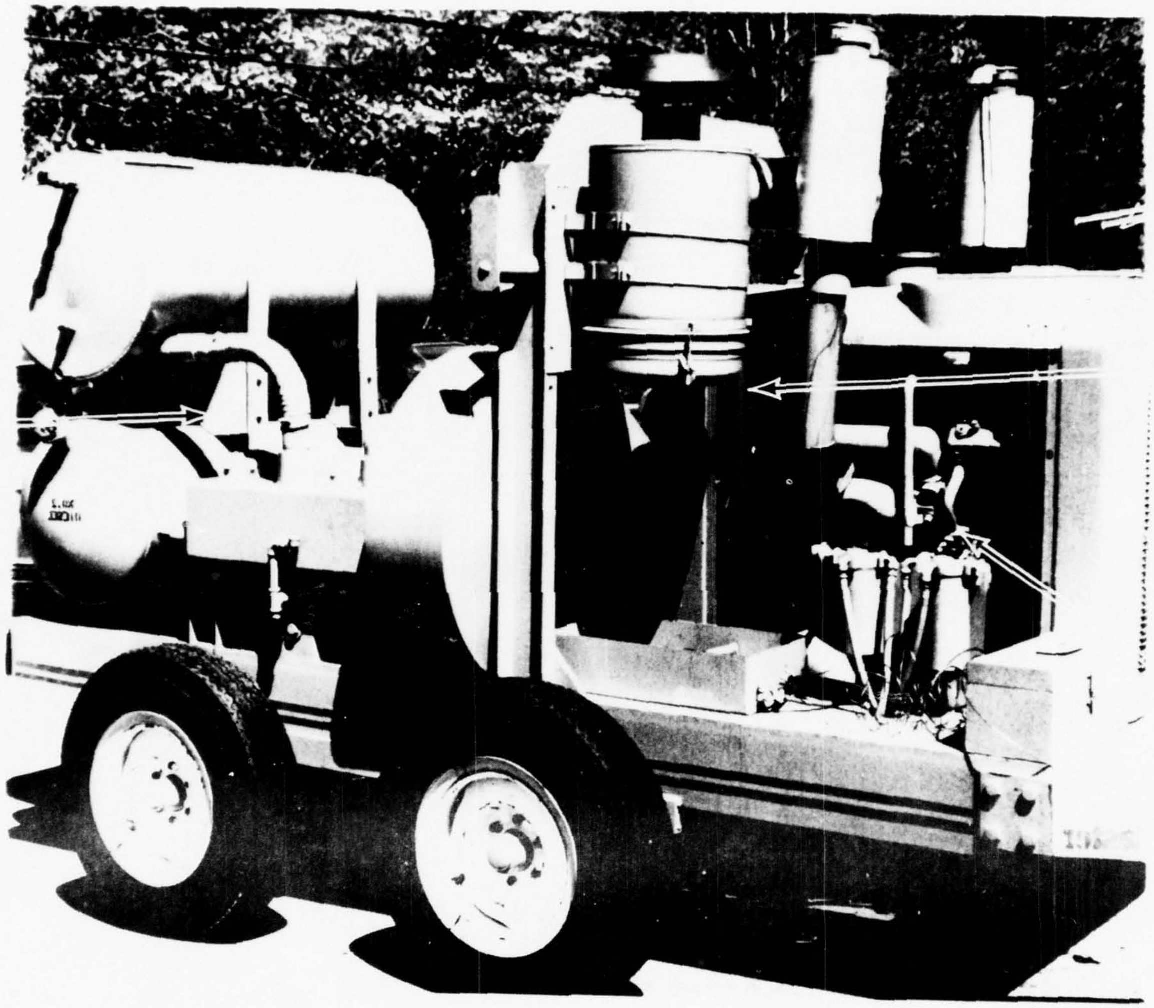


Figure 2 - Pump system for CAVIJET® nozzles: American Aero, Inc.
Model WBD-190V

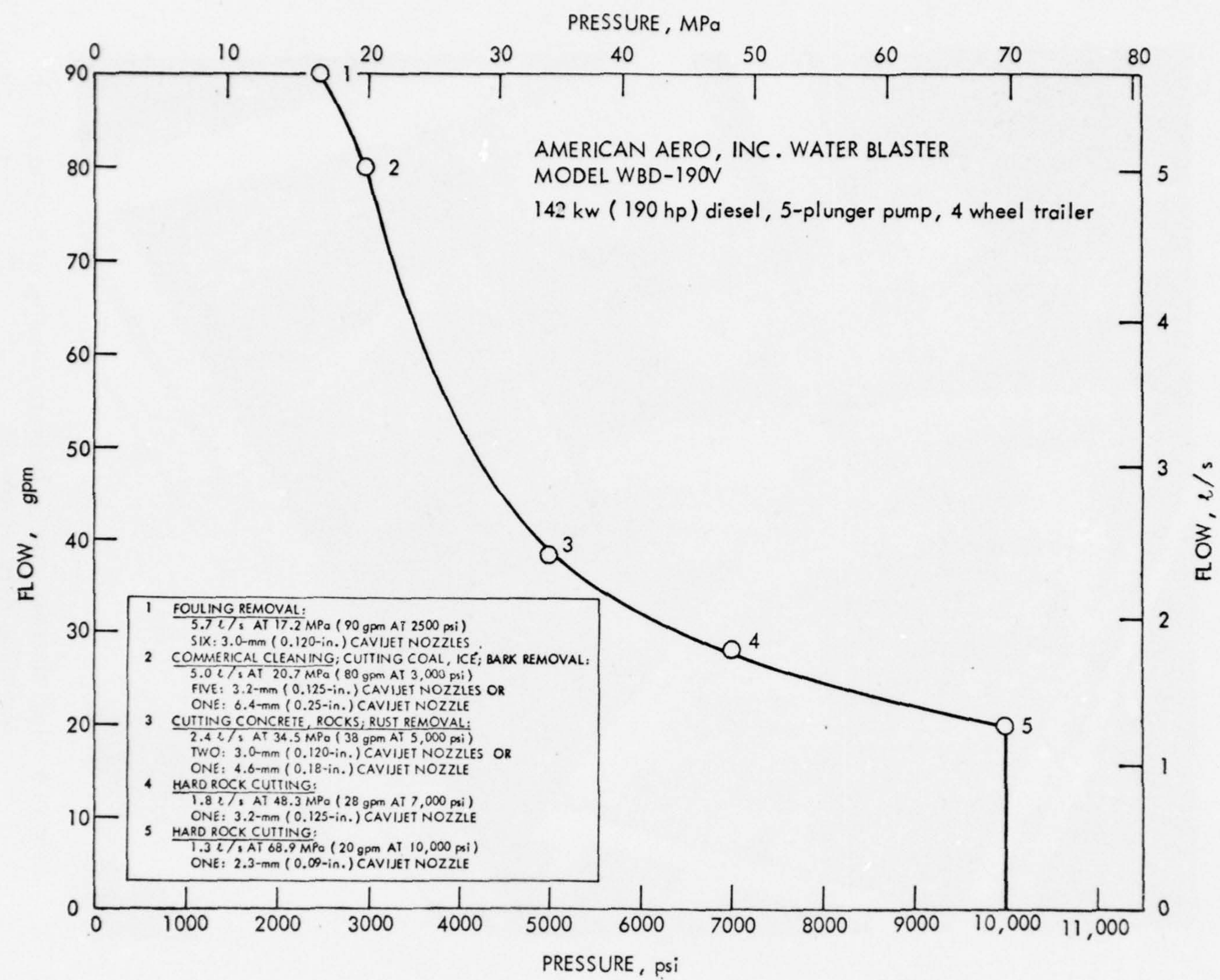


Figure 3 - Performance specifications of pump used for safety evaluations and laboratory testing.

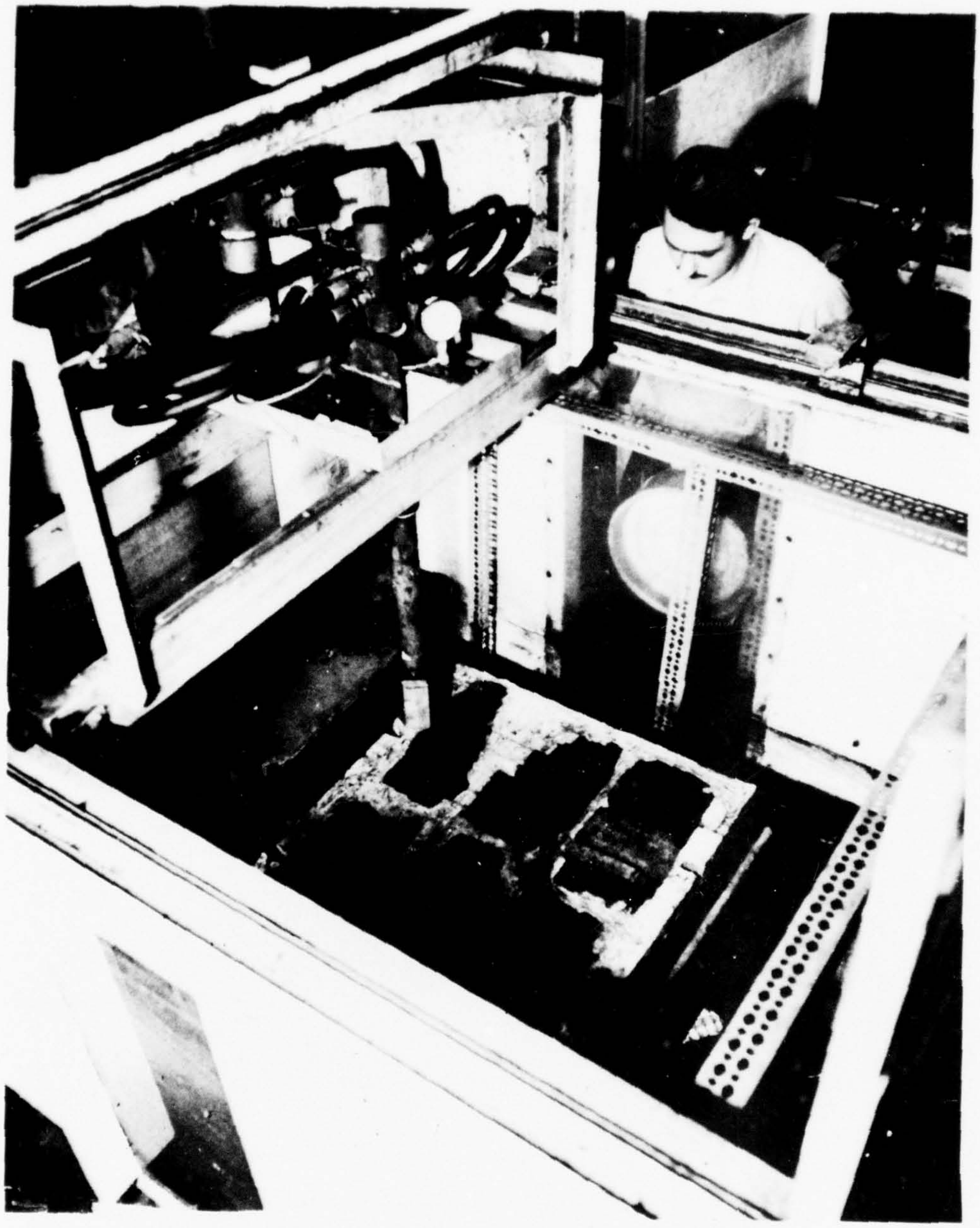


Figure 4 - Test chamber used for laboratory testing of the CAVIJET® cavitating fluid jet method.

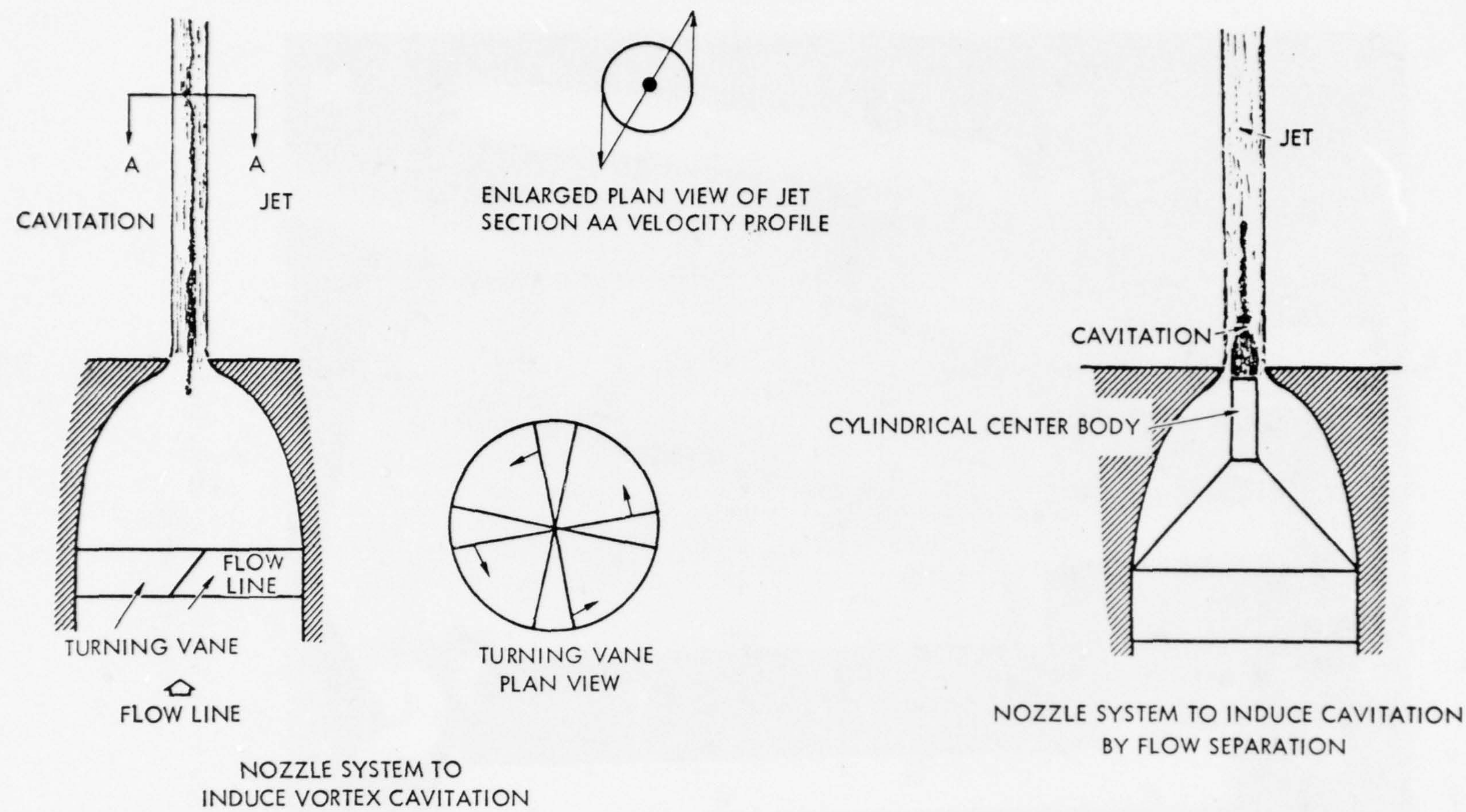


Figure 5 - Typical CAVIJET® cavitating fluid jet nozzle configurations.

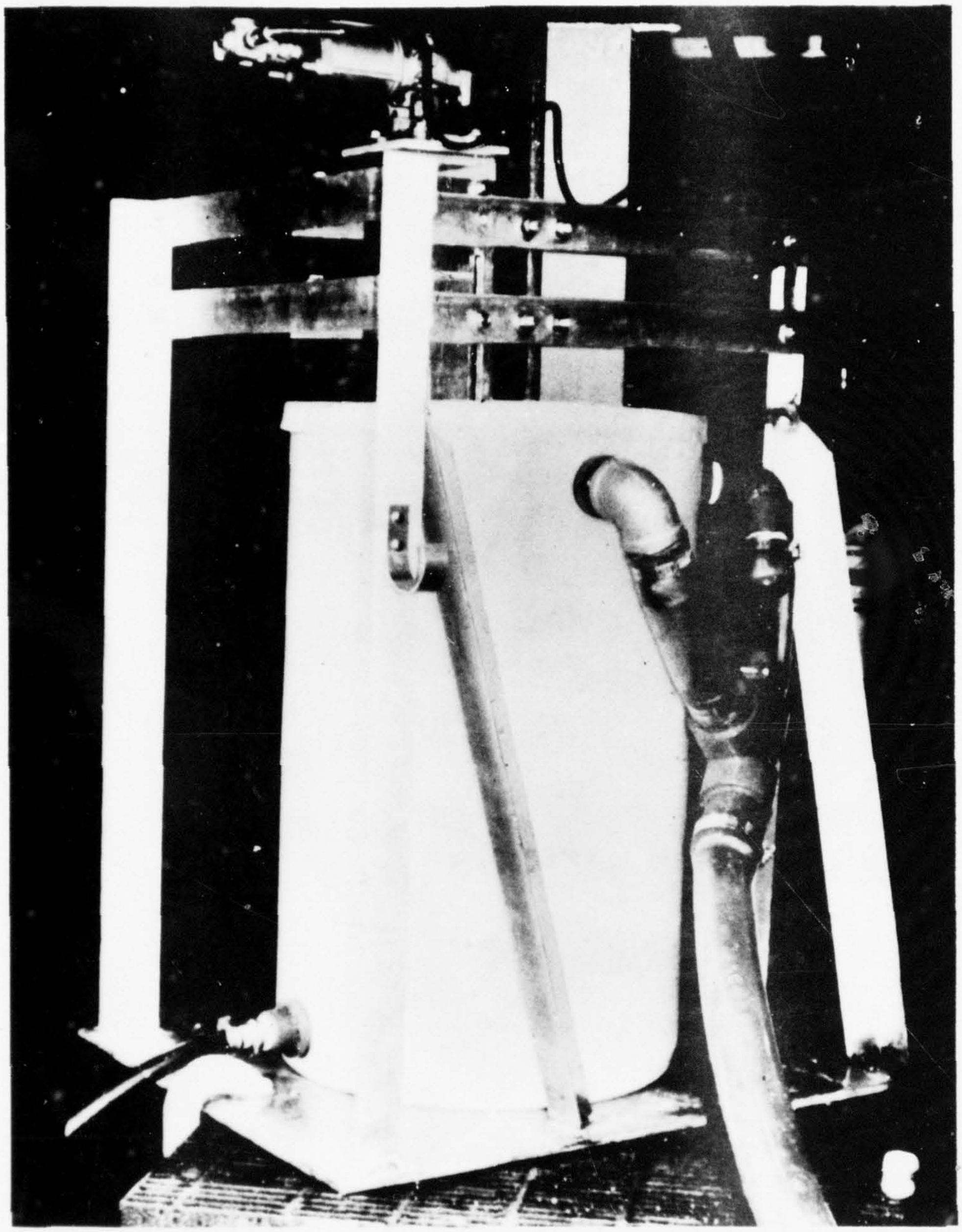


Figure 6 - Test stand used for safety evaluations of the CAVIJET® cavitating fluid jet.

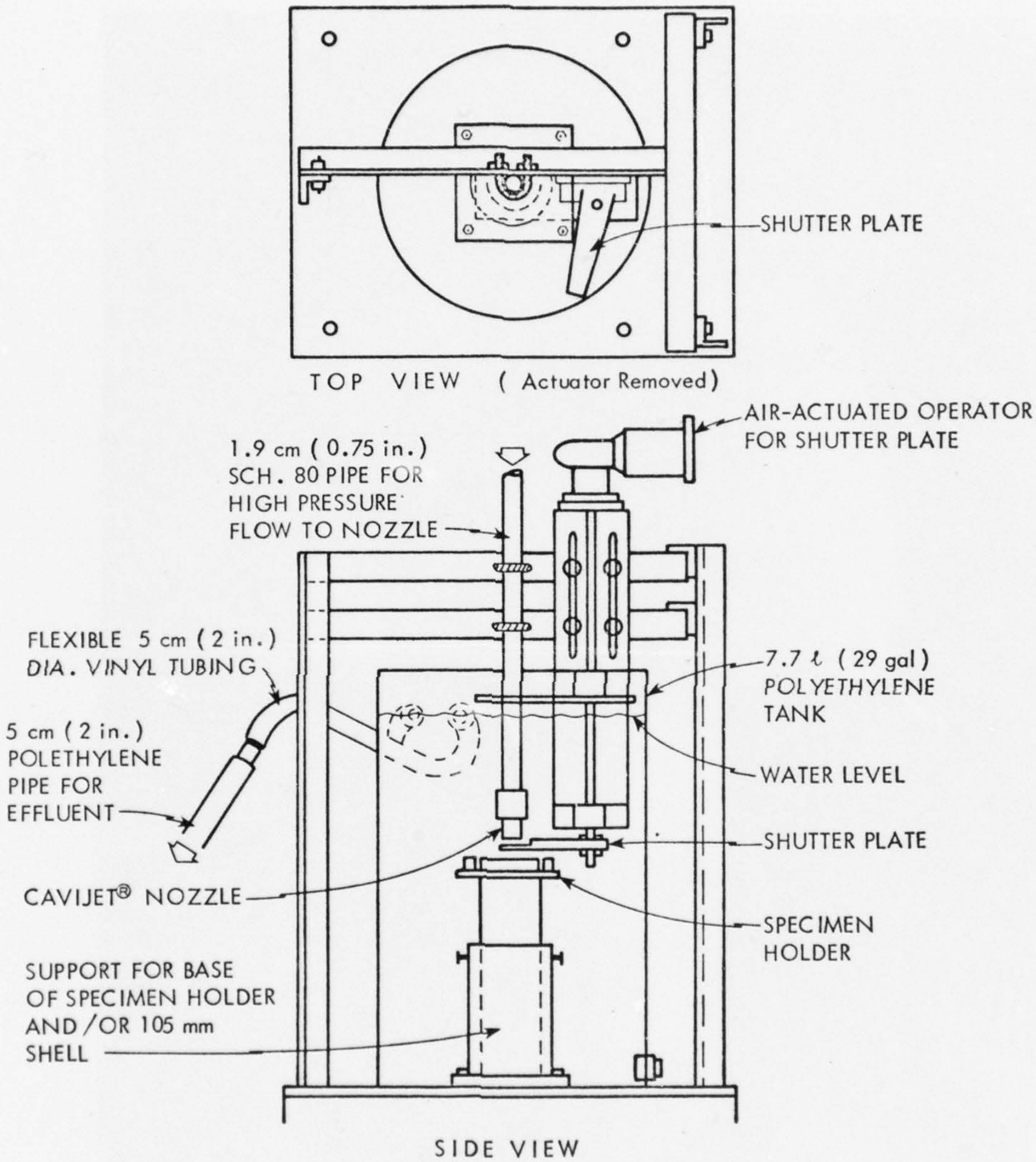


Figure 7 - Components of safety evaluations test stand.

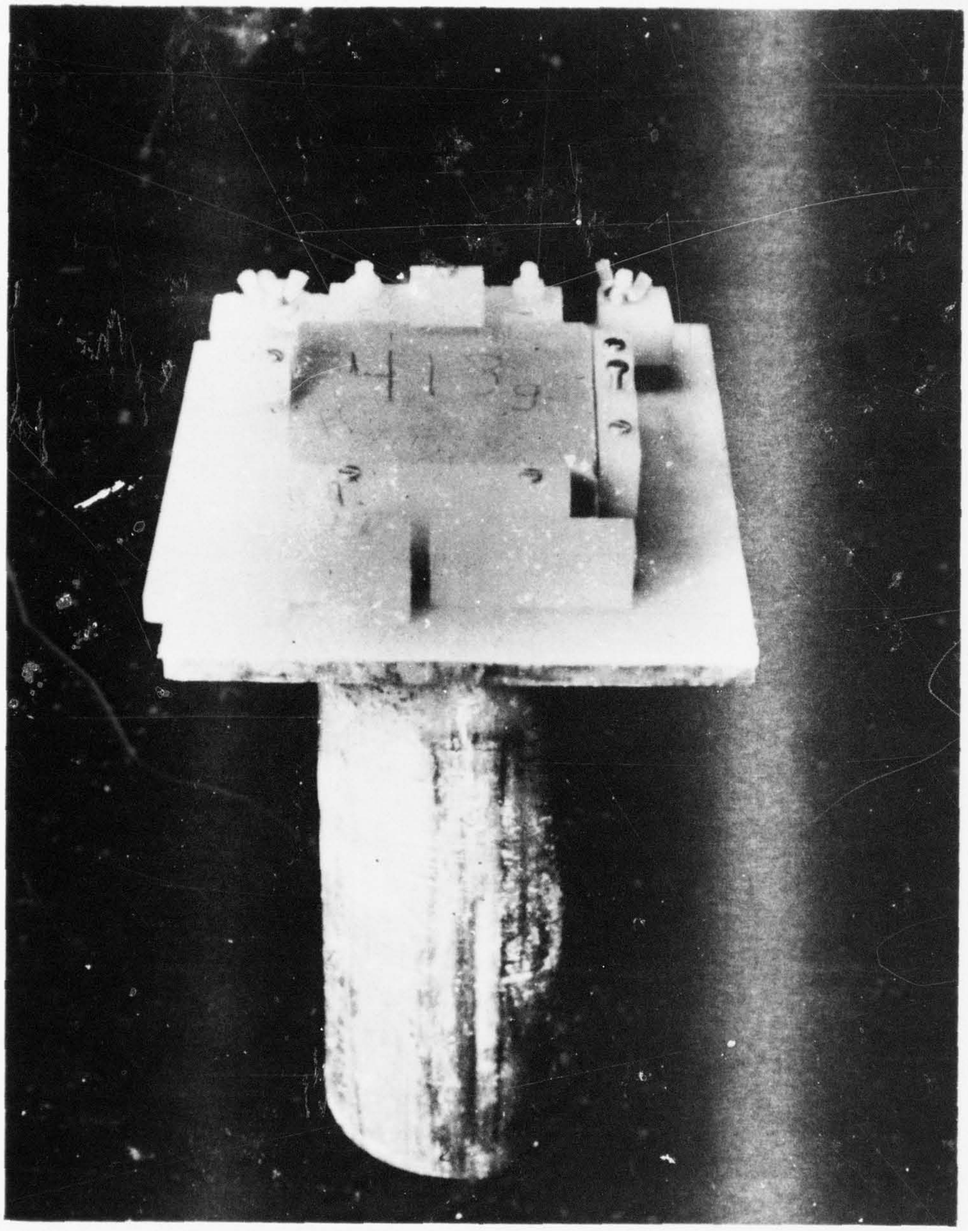


Figure 8 - Base and holder-support, with explosive specimen holder for top-orientation safety evaluations.

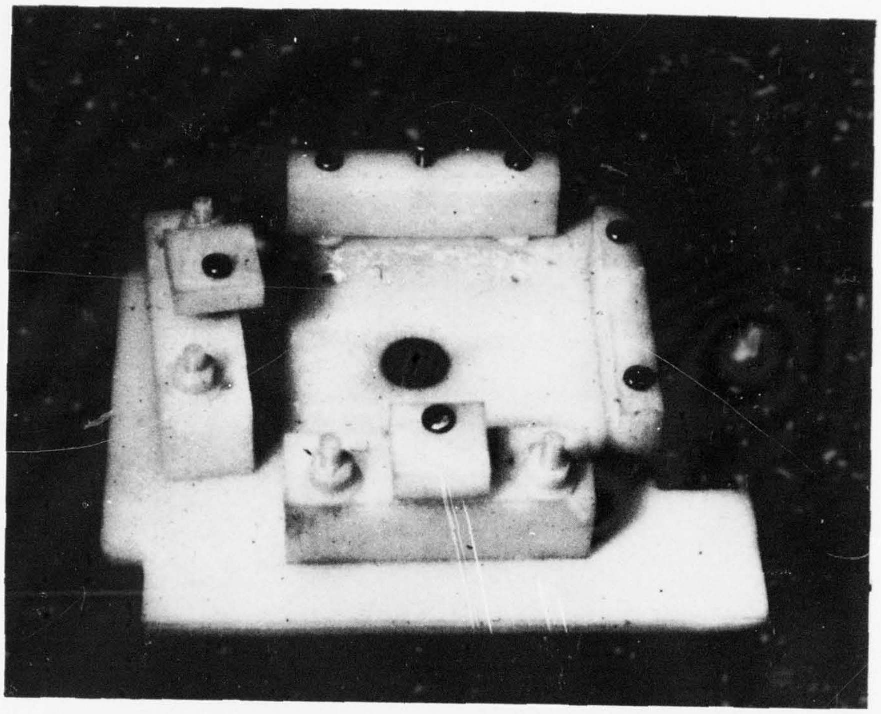


Figure 9 - Specimen holder for top-orientation (impingement on 2.5 cm (1 in.) thickness) safety evaluation tests.

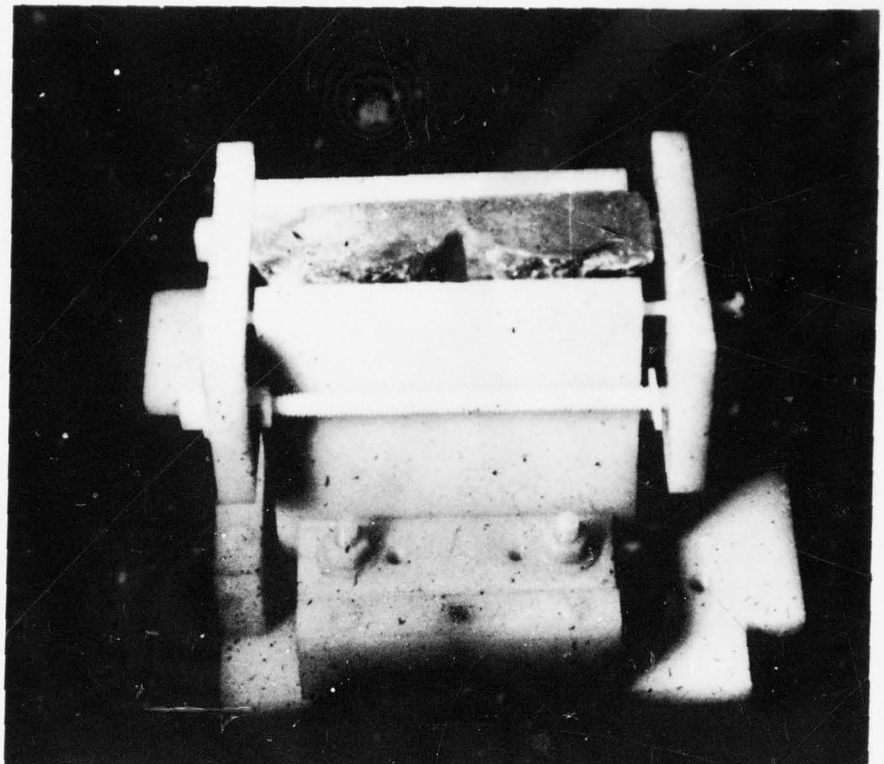


Figure 10 - Specimen holder for edge-orientation (impingement on 10 cm (4 in.) thickness) safety evaluation tests.

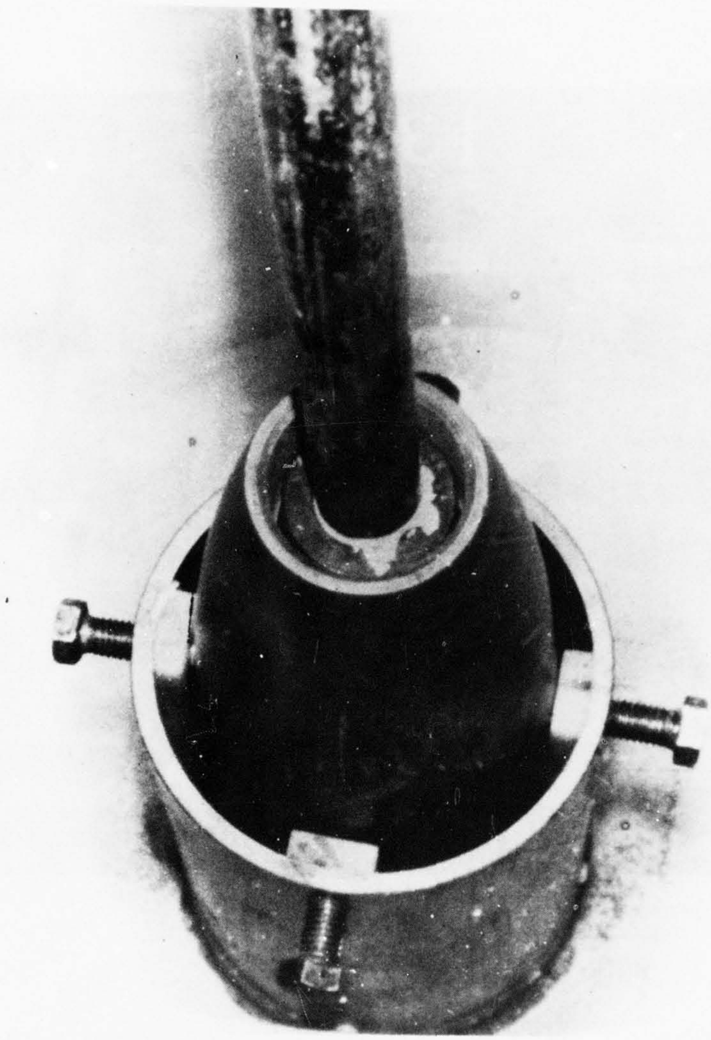


Figure 11 - 105-mm Shell with Composition B in test stand, ready for safety evaluation of 2.2 mm (0.086 in.) CAVIJET® nozzle.

Figure 12 - Typical TNT specimens tested in top-orientation with 2.2 mm (0.086 in.) CAVIJET® nozzle; pressure: 41.4 MPa (6 ksi); test durations: top row (left-to-right); 0.31, 0.21, 0.27 s, bottom row (left-to-right); 0.27, 0.25, 0.30 s; submerged mode; standoff: 2.2 cm (0.87 in.).

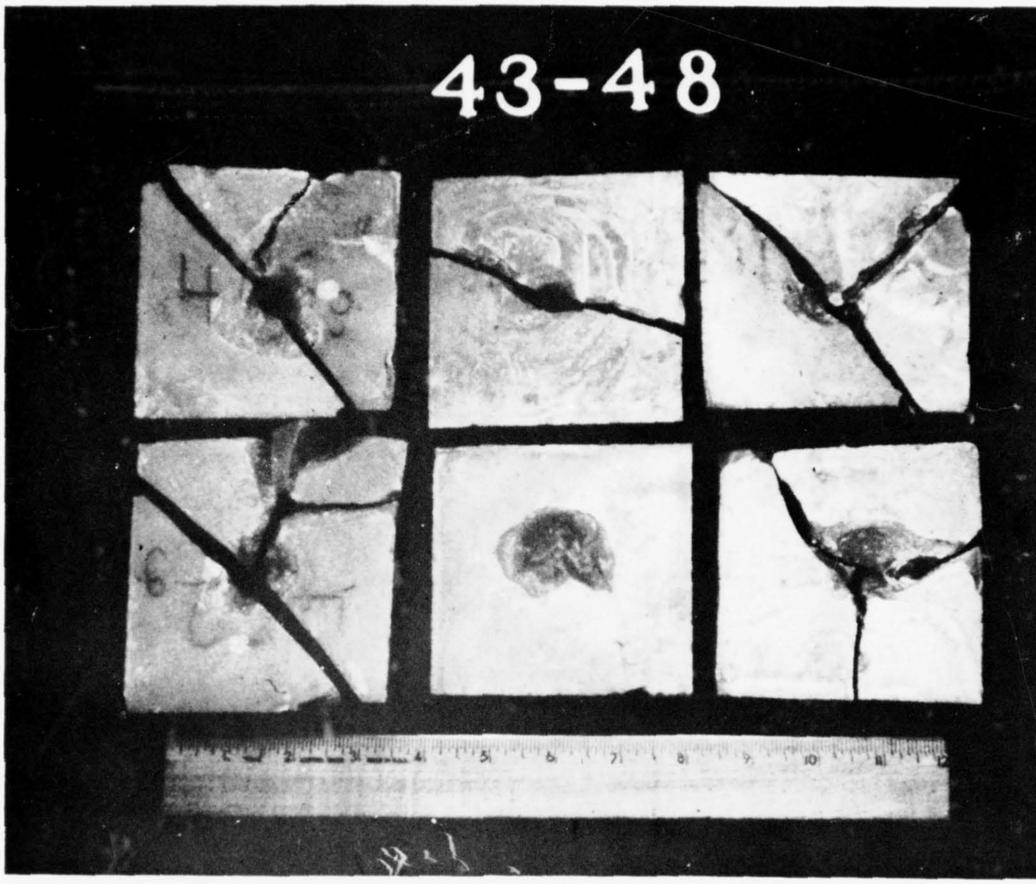


Figure 13 - Typical Composition B specimens tested in top orientation with 2.2 mm (0.086 in.) CAVIJET® nozzle; pressure: 41.4 MPa (6 ksi); test durations: top row (left-to-right): 0.29, 0.33, 0.31 s, bottom row (left-to-right): 0.31, 0.19, 0.33 s; submerged mode; standoff: 2.2 cm (0.87 in.).

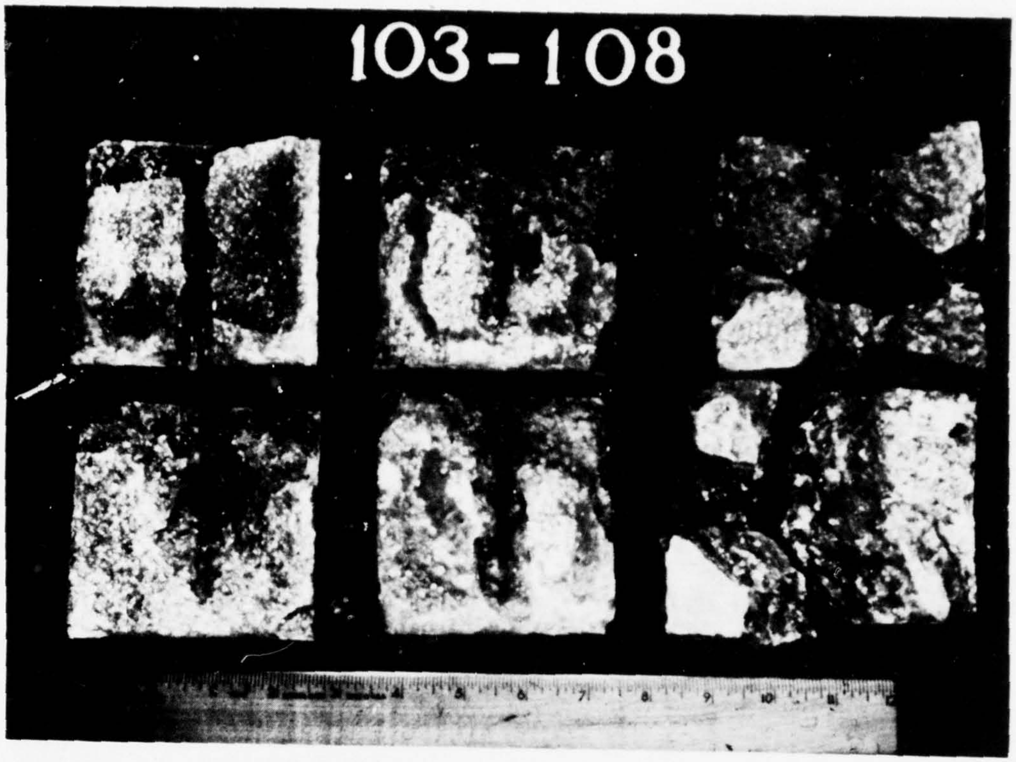


Figure 14 - Typical TNT specimens tested in edge orientation with 2.2 mm (0.086 in.) CAVIJET® nozzle; pressure: 41.4 MPa (6 ksi); test durations; top row (left-to-right): 1.03, 0.51, 0.59 s, bottom row (left-to-right): 0.47, 0.56, 0.46 s; submerged mode; standoff: 2.2 cm (0.87 in.)

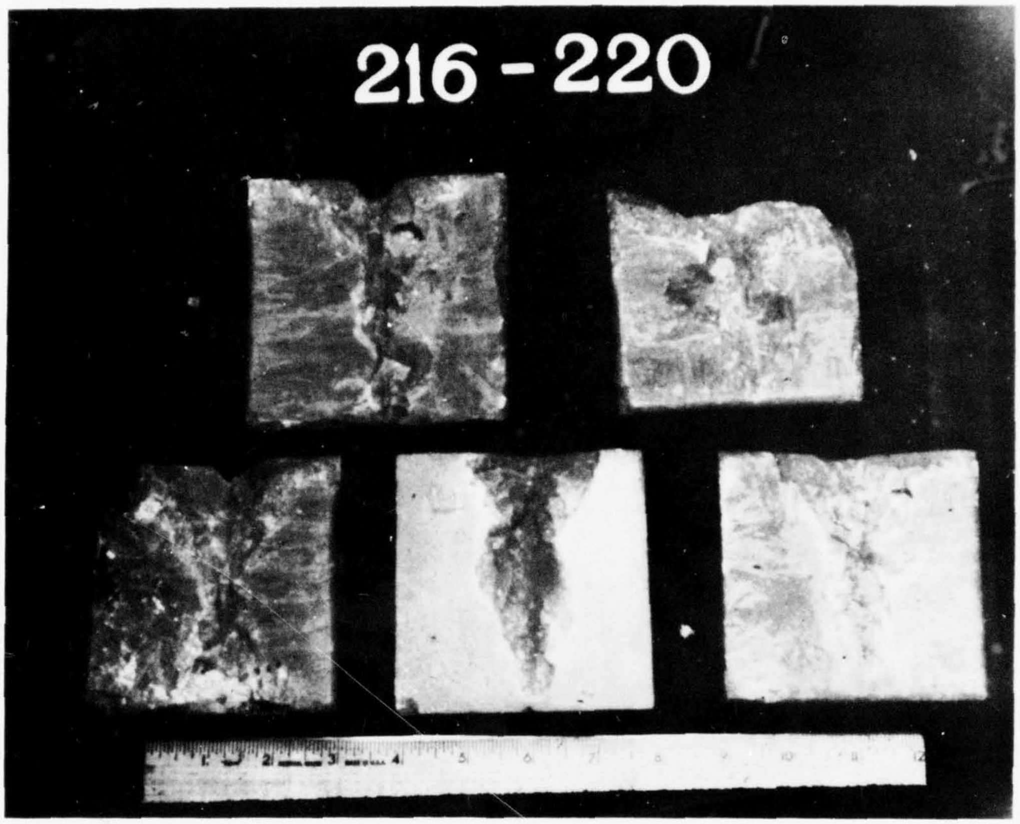


Figure 15 – Typical Composition B specimens tested in edge orientation with 2.2 mm (0.086 in.) CAVIJET® nozzle; pressure: 68.9 MPa (10 ksi); test durations: top row (left-to-right): 0.38, 0.23 s, bottom row (left-to-right): 0.29, 0.27, 0.22 s; in-air mode; standoff: 2.2 cm (0.87 in.)

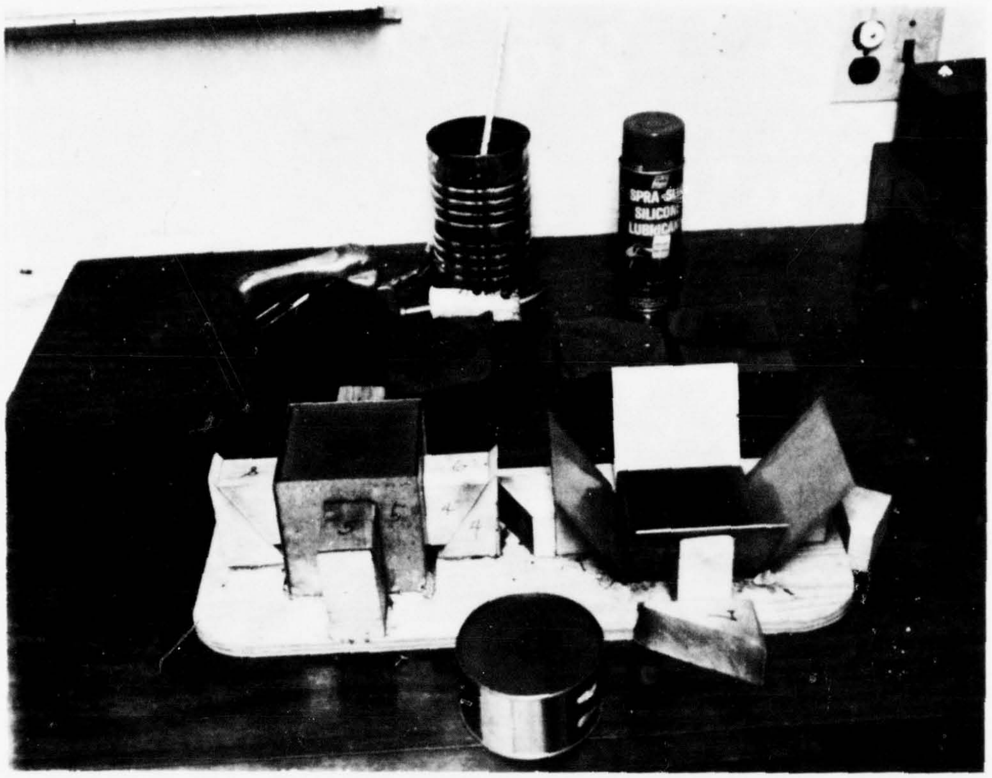


Figure 16 - Molds for casting inert explosive simulant specimens.

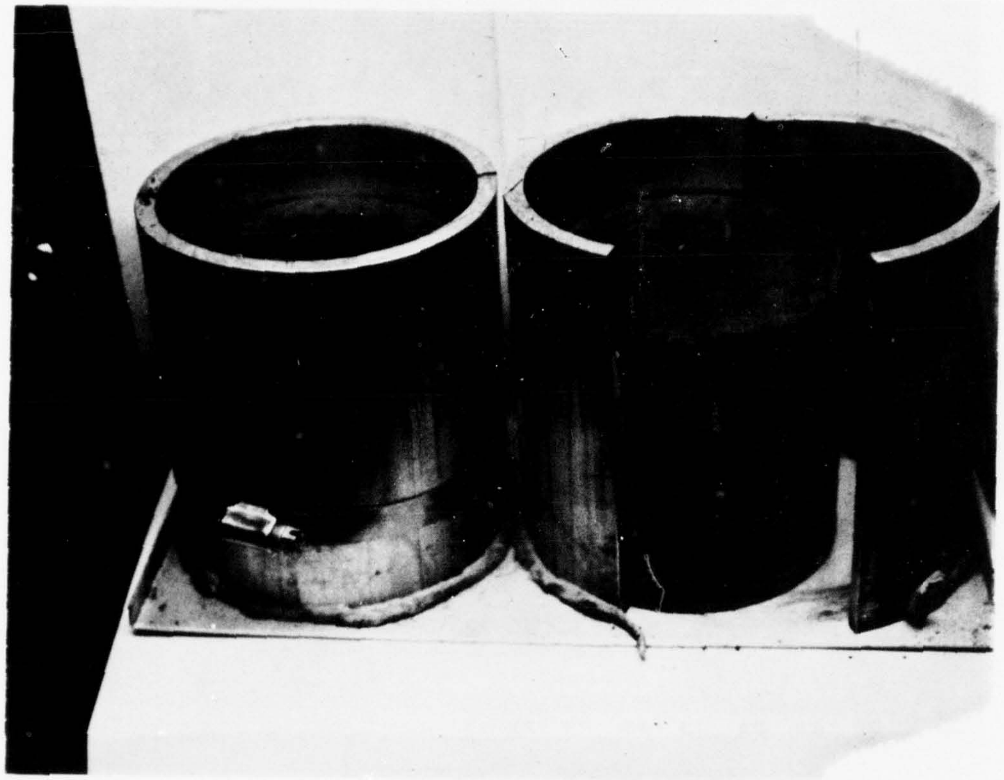
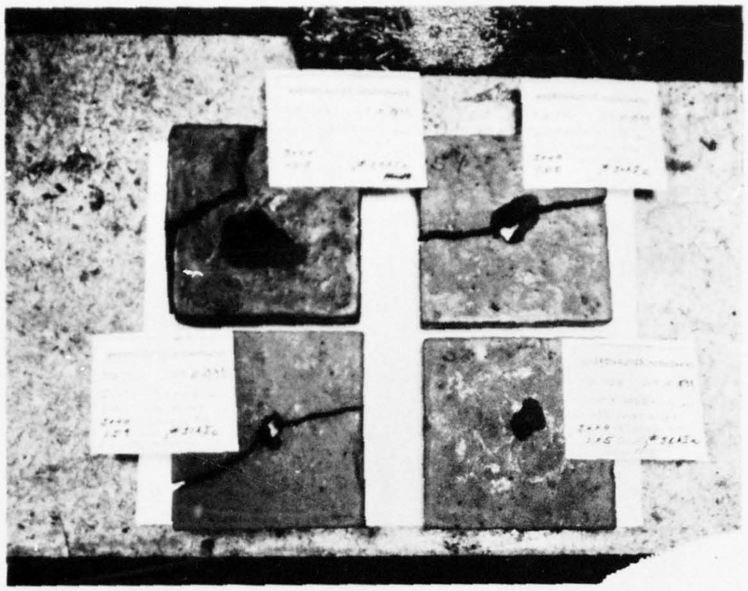


Figure 17 - Molds for casting cylindrical specimens of inert filler with 60 percent sand mixture.

Figure 18 - Typical results of translating tests on specimens of inert filler without sand; runs at 13.8 MPa (2 ksi), translation velocities 1.3 to 30 cm / s (0.5 to 12 in. / s); plain 3.2 mm (0.125 in.) CAVIJET® nozzle, submerged.



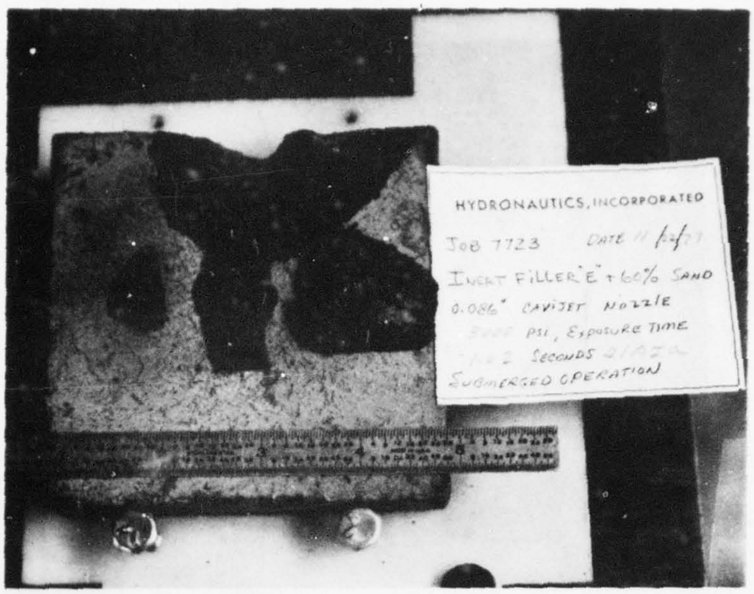
a. Pressure: 20.7 MPa (3 ksi), test durations: 0.5 to 1.0 s.

b. Pressure: 31.0 MPa (4.5 ksi), test duration: 0.54 s.

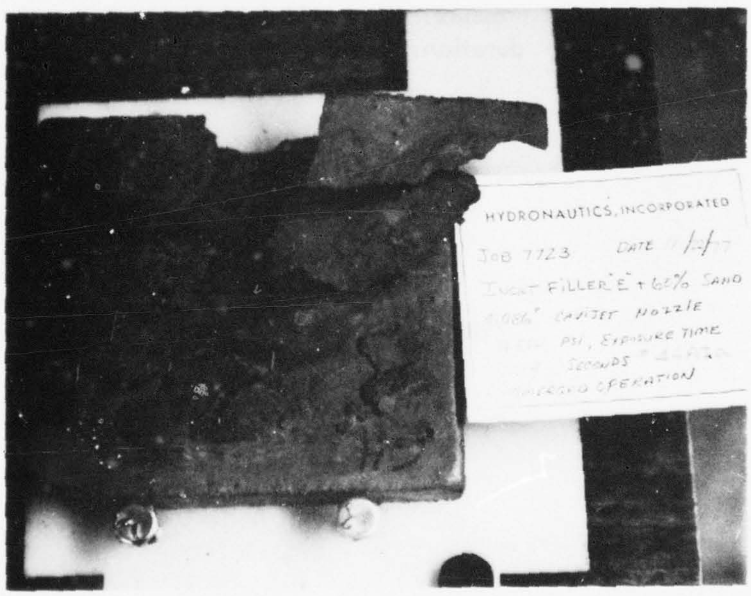
Figure 19 - Stationary tests using top orientation, inert filler with 60 percent sand mixture; 2.2 mm (0.086 in.) CAVIJET® nozzle, submerged.

c. Pressure: 41.4 MPa (6 ksi), test
duration: 0.33 s

Figure 19 - Concluded



a. Pressure: 20.7 MPa (3 ksi), test
duration: 1.02 s.



b. Pressure: 31.0 MPa (4.5 ksi), test
duration: 1.09 s.

Figure 20 - Stationary tests using edge orientation, inert filler with 60 percent sand mixture; 2.2 mm (0.086 in.) CAVIJET® nozzle, submerged.

c. Pressure: 41.4 MPa (6 ksi), test duration: 0.48 s.

Figure 20 - Concluded

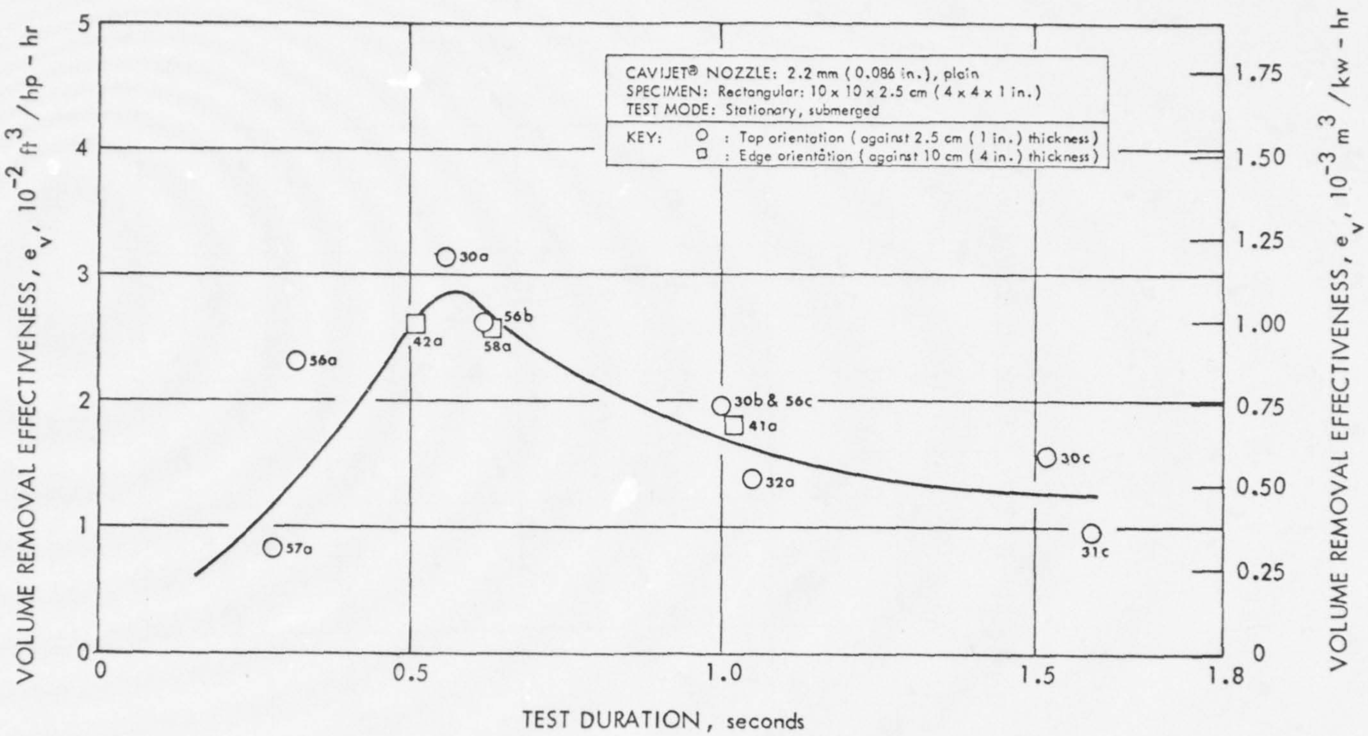


Figure 21 - Time dependence of volume removal effectiveness: inert filler with 60 percent sand, 20.7 MPa (3 ksi).

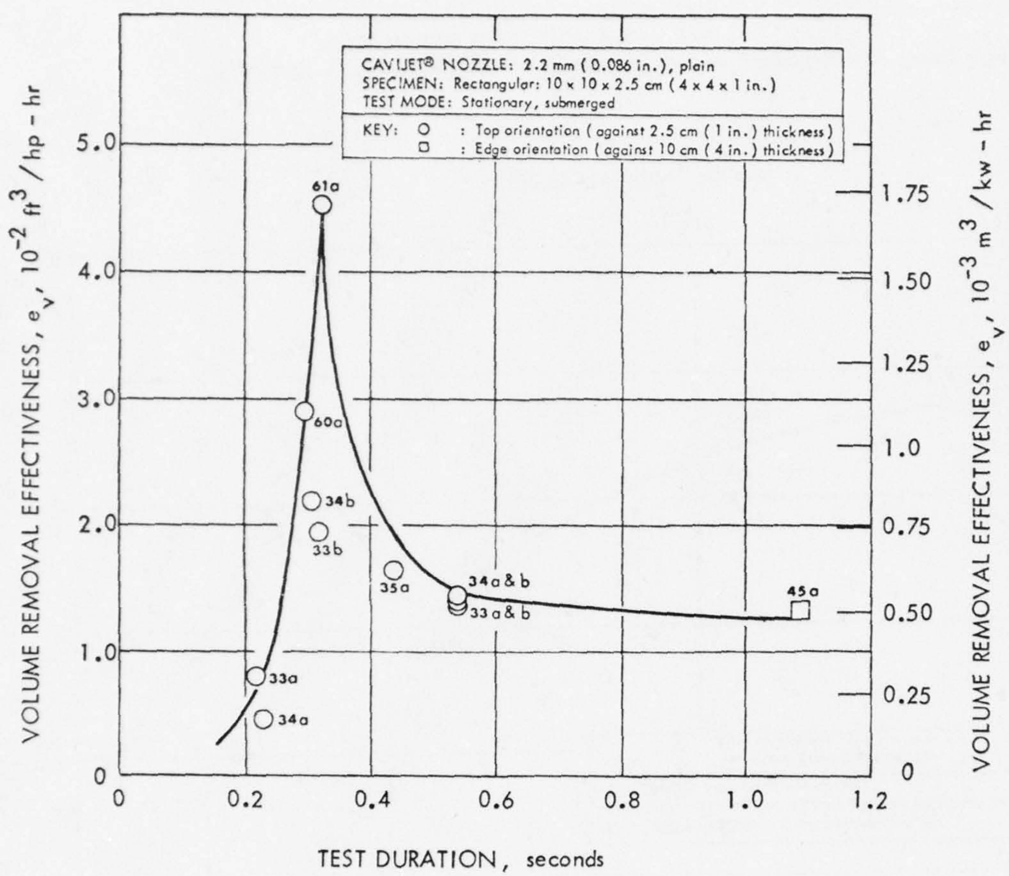


Figure 22 - Time dependence of volume removal effectiveness: inert filler with 60 percent sand, 31.0 MPa (4.5 ksi).

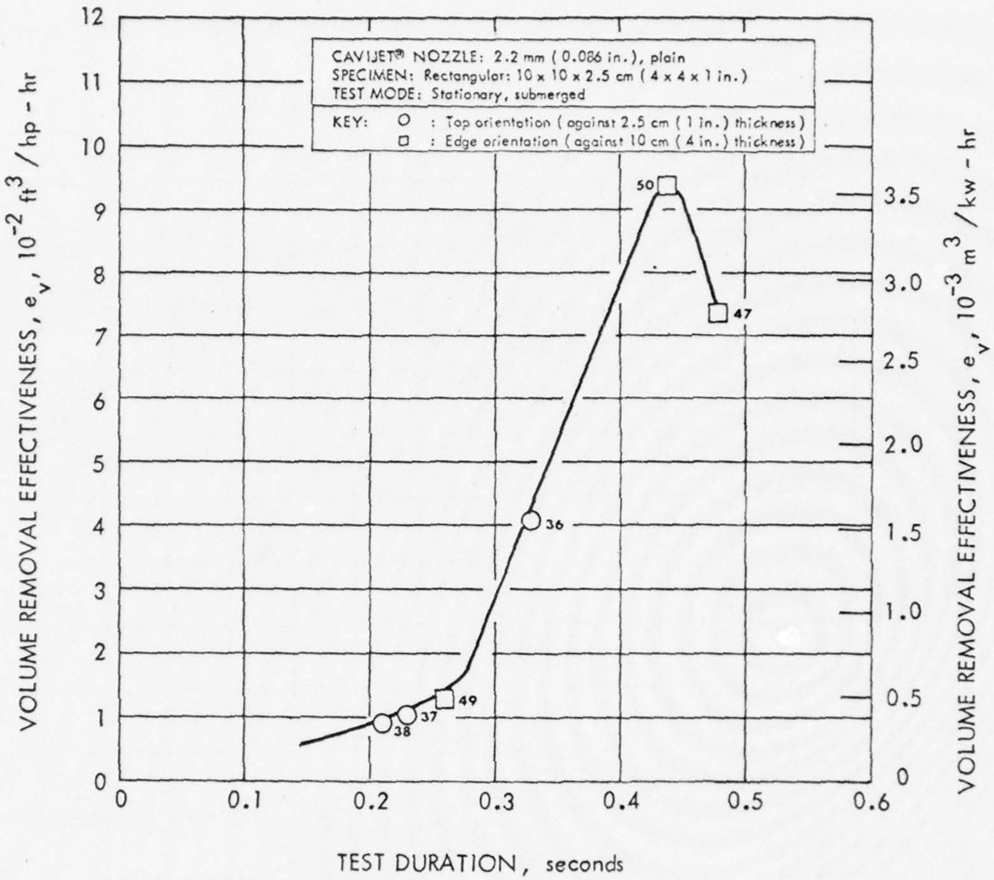


Figure 23 - Time dependence of volume removal effectiveness: inert filler with 60 percent sand, 41.4 MPa (6 ksi).

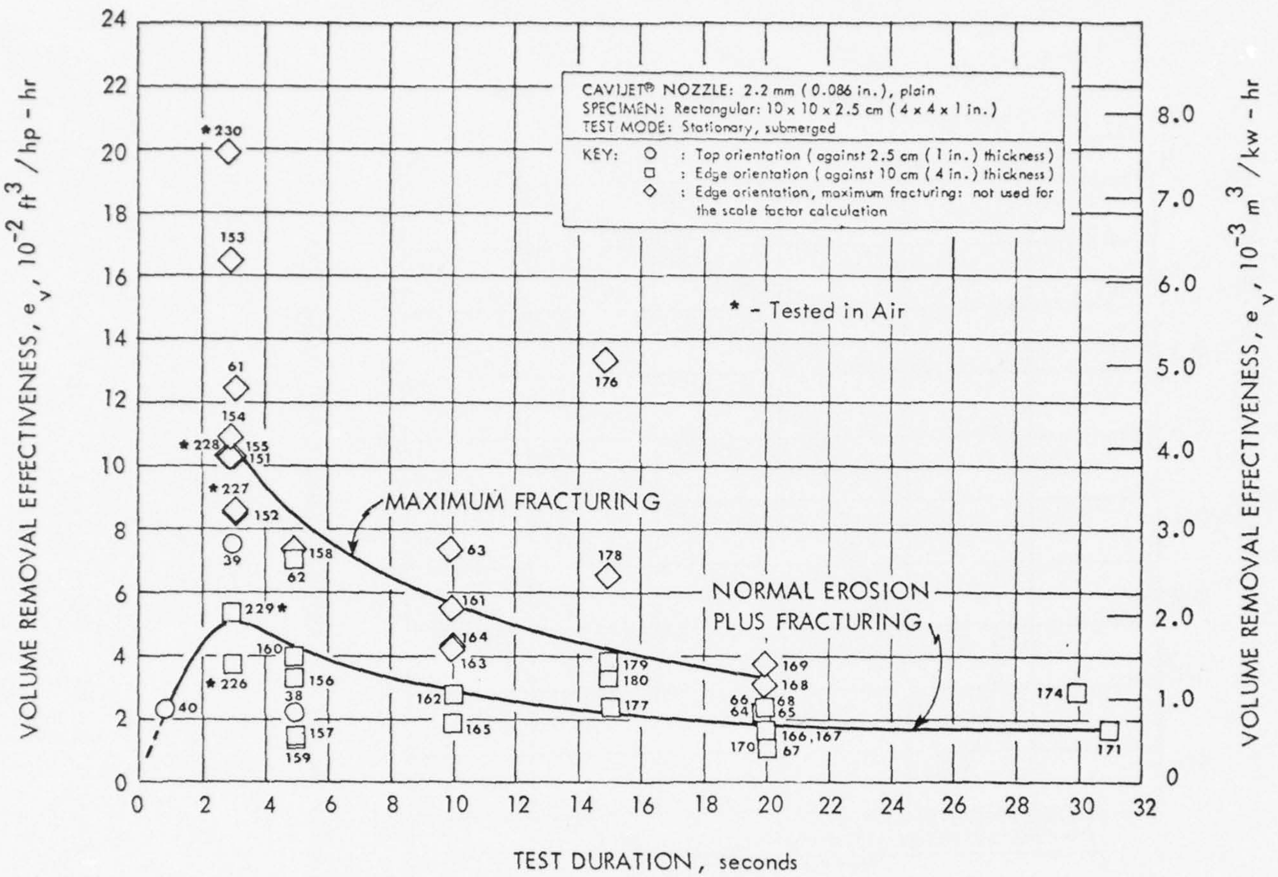


Figure 24 - Time dependence of volume removal effectiveness: Composition B explosive, 20.7 MPa (3 ksi).

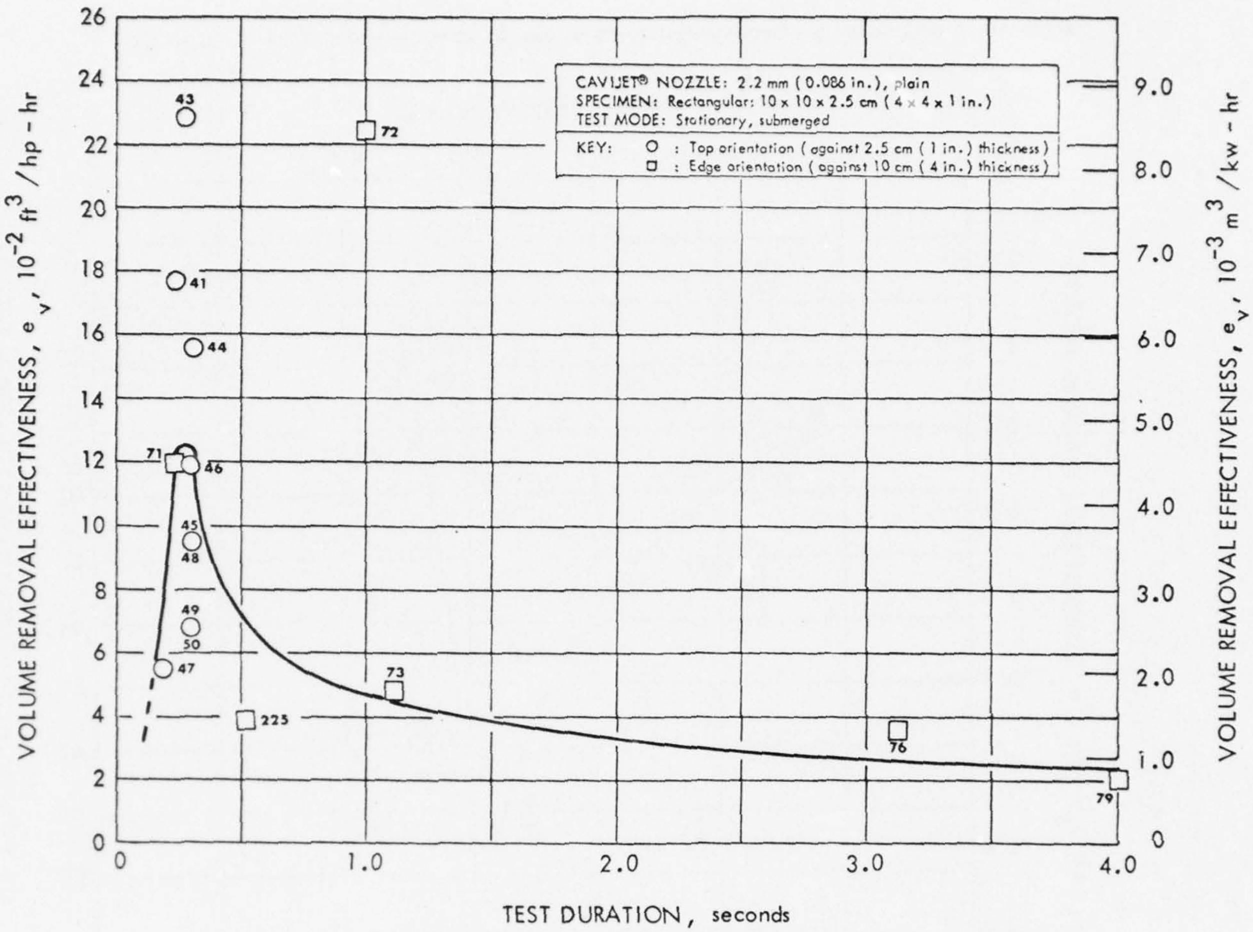


Figure 25 - Time dependence of volume removal effectiveness: Composition B explosive, 41.4 MPa (6 ksi).

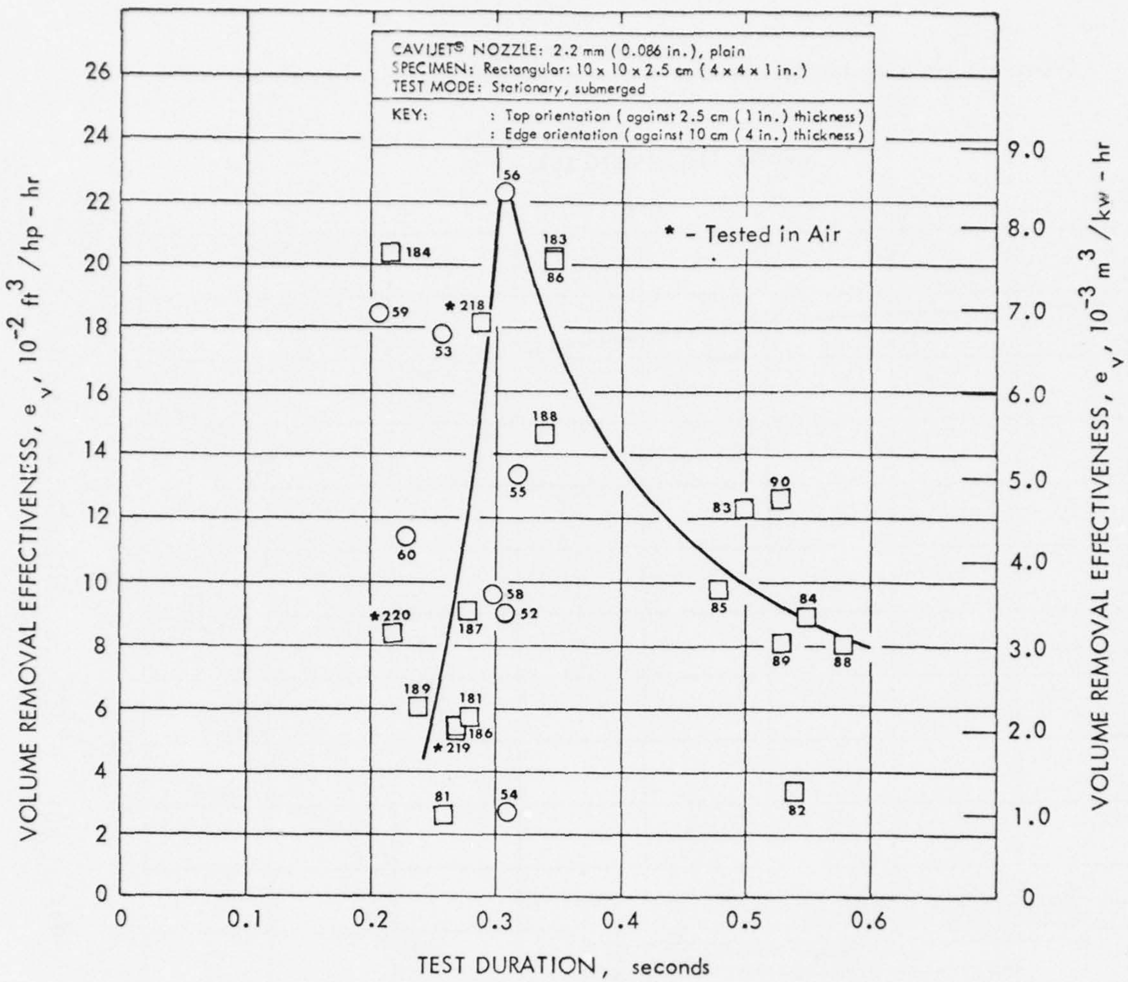


Figure 26 - Time dependence of volume removal effectiveness: Composition B explosive, 68.9 MPa (10 ksi).

CAVIJET® NOZZLE: 2.2 mm (0.086 in.), plain
SPECIMEN: Rectangular: 10 x 10 x 2.5 cm (4 x 4 x 1 in.)
TEST MODE: Stationary, submerged

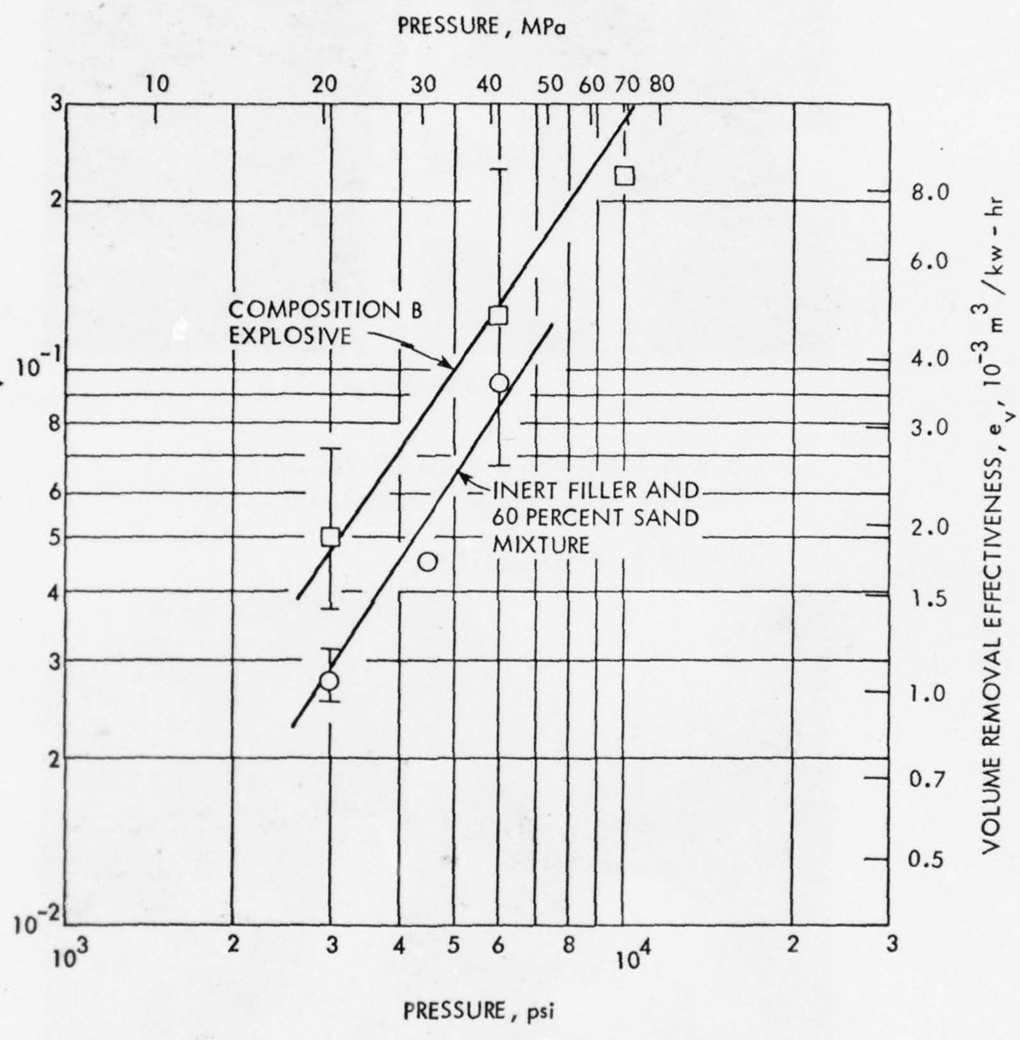
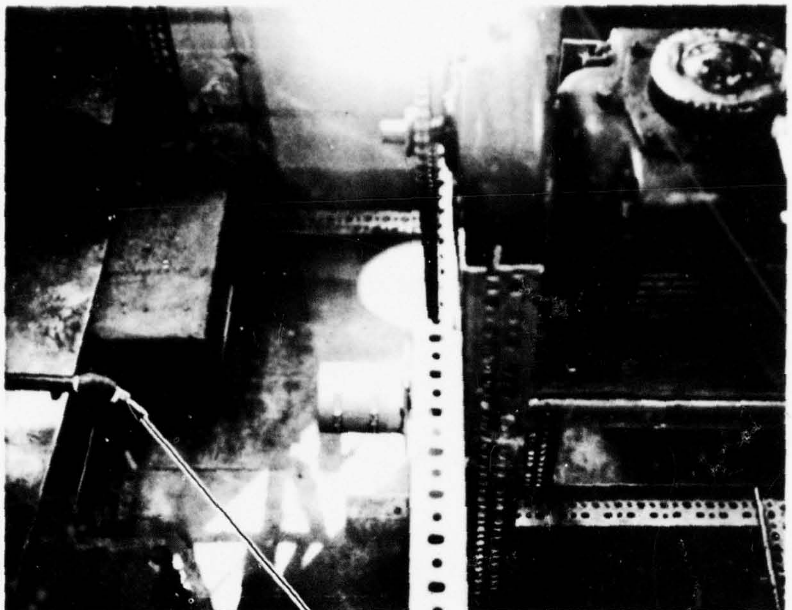
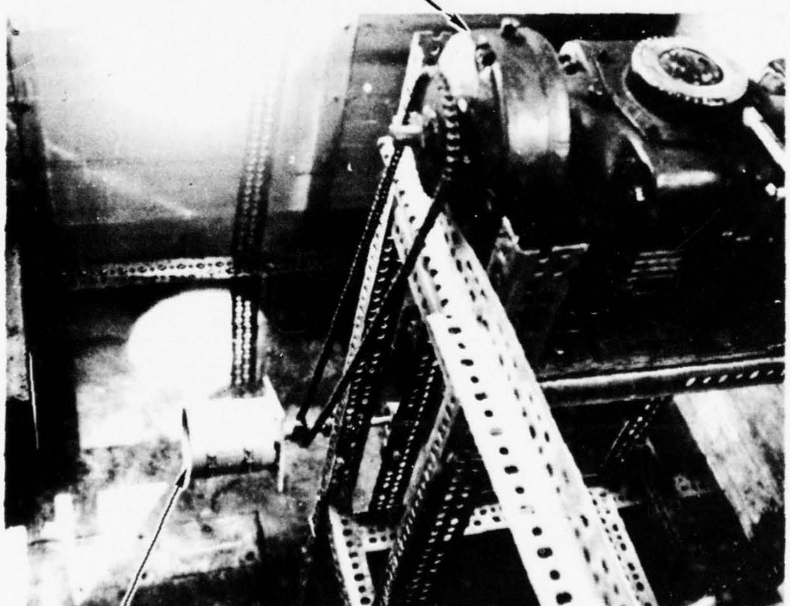


Figure 27 - Comparison of peak values of volume removal effectivess: for scale factor calculation.

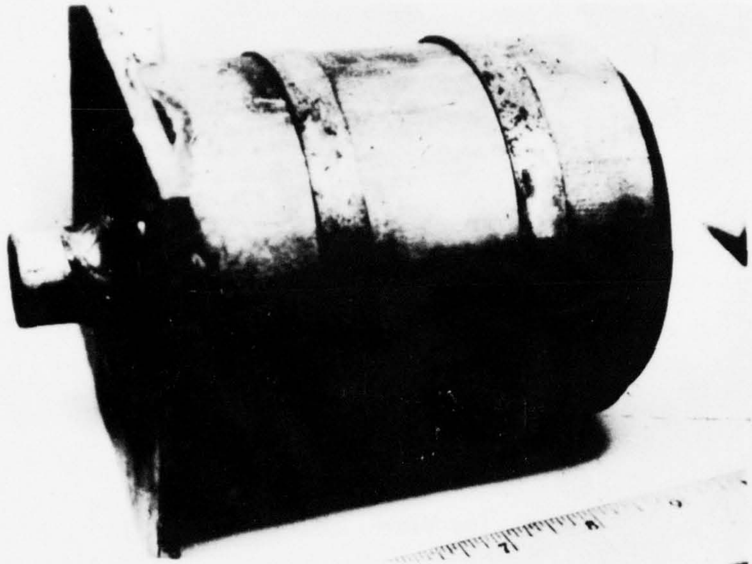


a. Overall view with 3.2 mm (0.125 in.) CAVIJET nozzle at 30° impingement angle.



b. Variable speed motor and specimen holder.

Figure 28 - Rotating test configuration to simulate CAVIJET® cavitating fluid jet washout of munitions.



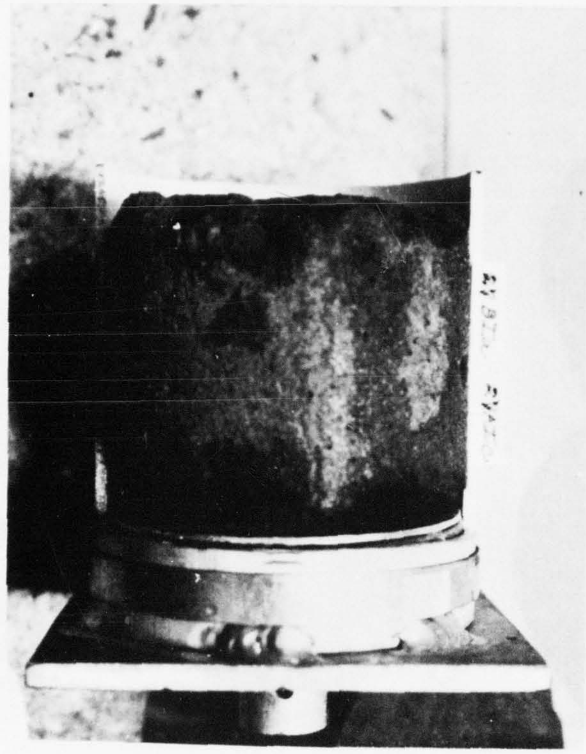
c. Closeup of cylindrical specimen holder.

Figure 28 - Concluded

a. Top View: 20.7 MPa (3 ksi)

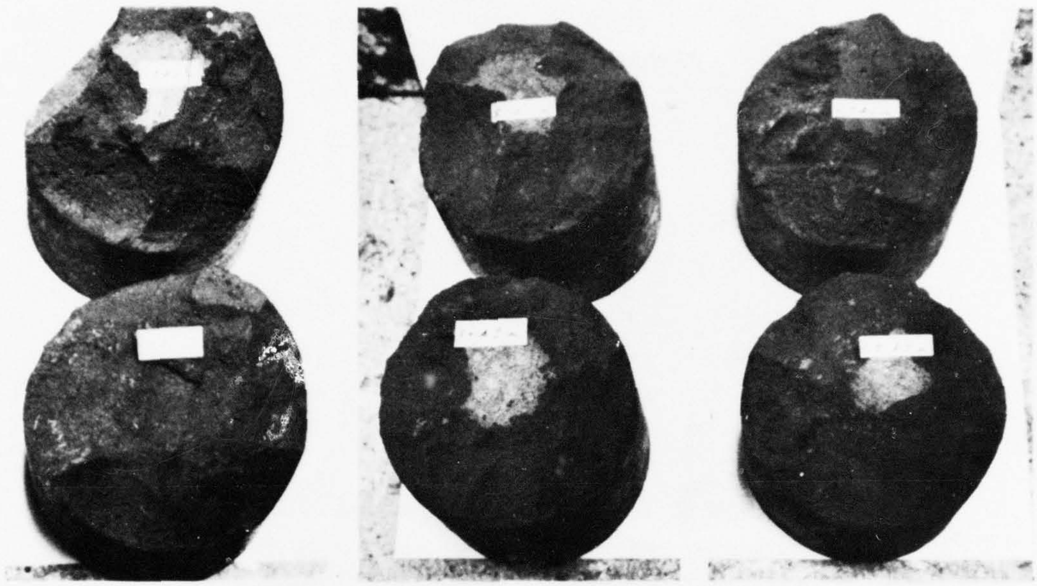
b. Top View: 27.6 MPa (4 ksi)

Figure 29 - Preliminary rotating test specimens, inert filler with 60 percent sand; plain 3.2 mm (0.125 in.) CAVIJET® nozzle, 45° impingement angle, submerged, 40 RPM, nozzle translation rate: 8.4 mm/s (0.33 in./s).



c. Side View: 27.6 MPa (4 ksi)

Figure 29 - Concluded



20.7 MPa (3 ksi)   27.6 MPa (4 ksi)   34.5 MPa (5 ksi)

Figure 30 - Effect of pressure in preliminary rotating tests; plain 3.2 mm (0.125 in.) CAVIJET® nozzle, 30° impingement angle, submerged, 20 RPM, nozzle translation rate: 8.4 mm / s (0.33 in. / s).

SPECIMEN: Inert filler / 60 percent sand
Cylinder: 10 cm dia. x 10 cm long (4 x 4 in.)
TEST MODE: Rotating, submerged
ROTATION RATE: 20 RPM
NOZZLE TRANSLATION RATE: 8.4 mm / s (0.33 in. / s)
IMPINGEMENT ANGLE: 30°

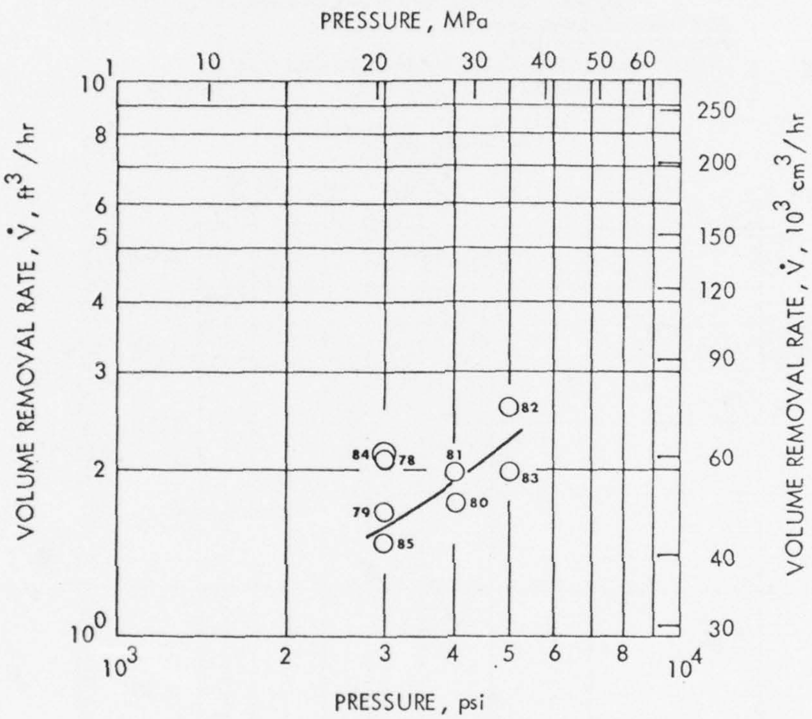


Figure 31 - Pressure dependence of volume removal rate in preliminary rotating tests; plain 3.2 mm (0.125 in.) CAVIJET® nozzle.

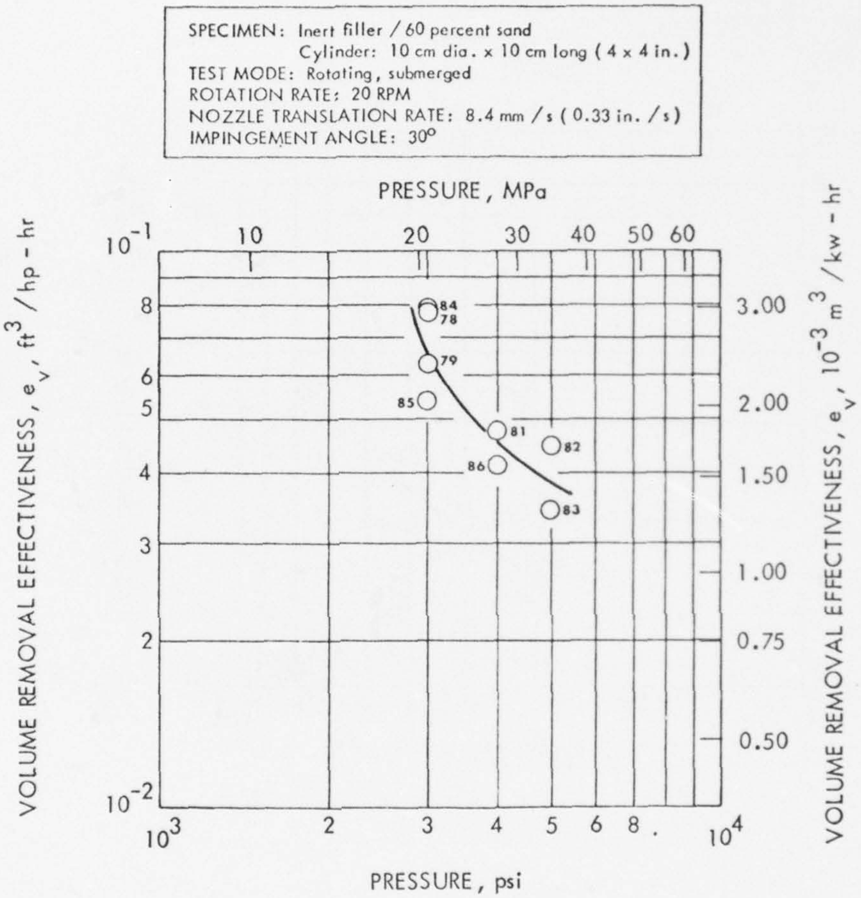


Figure 32 - Pressure dependence of volume removal effectiveness in preliminary rotating tests; plain 3.2 mm (0.125 in.) CAVIJET® nozzle.

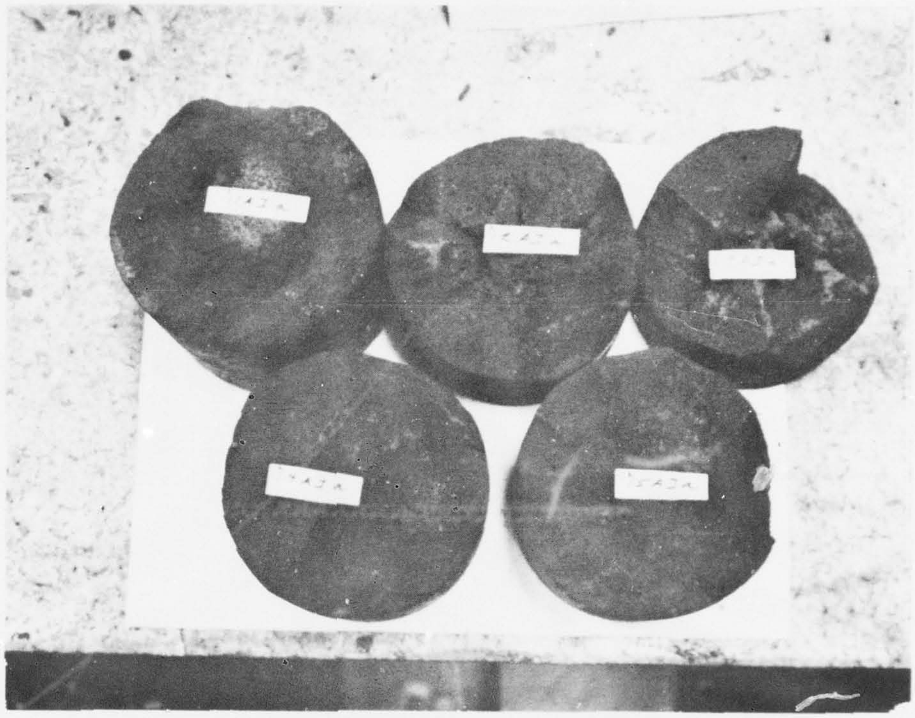


Figure 33 - Effect of pressure in preliminary rotating tests; plain 3.6 mm (0.140 in.) CAVIJET® nozzle, 30° impingement angle, submerged, 20 RPM, nozzle translation rate: 8.4 mm / s (0.33 in. / s); top row: 34.5 MPa (5 ksi) bottom row: 27.6 MPa (4 ksi).

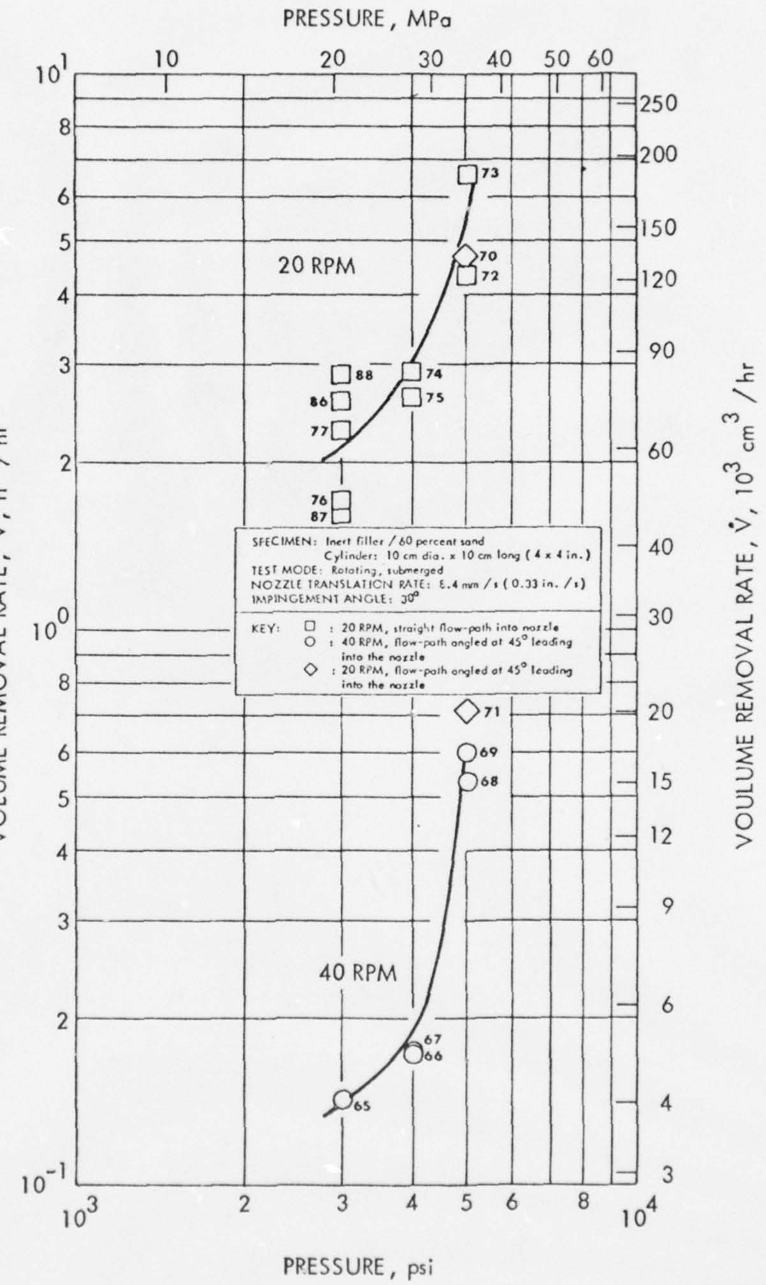


Figure 34 - Pressure dependence of volume removal rate in preliminary rotating tests; plain 3.6 mm (0.140 in.) CAVIJET® nozzles.

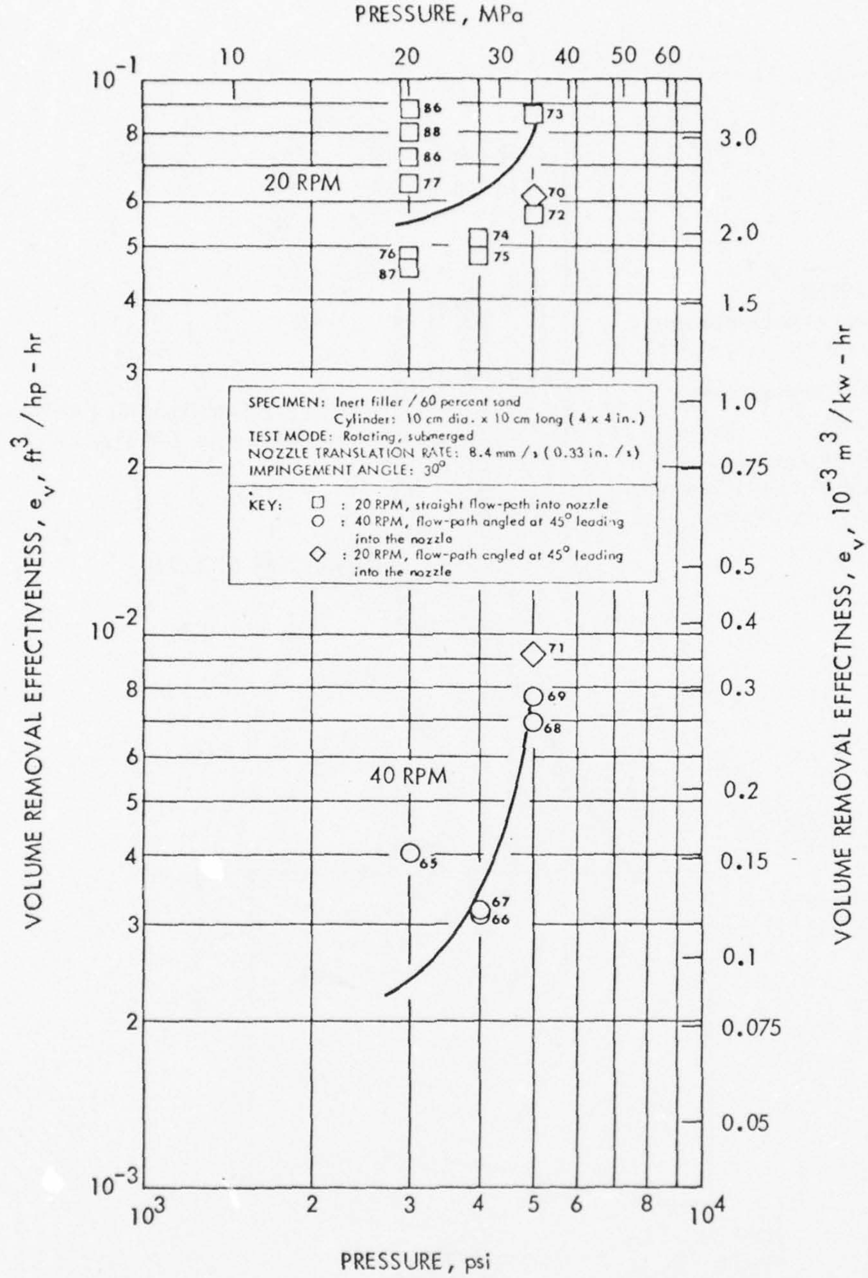


Figure 35 - Pressure dependence of volume removal effectiveness in preliminary rotating tests; plain 3.6 mm (0.140 in.) CAVIJET® nozzles.

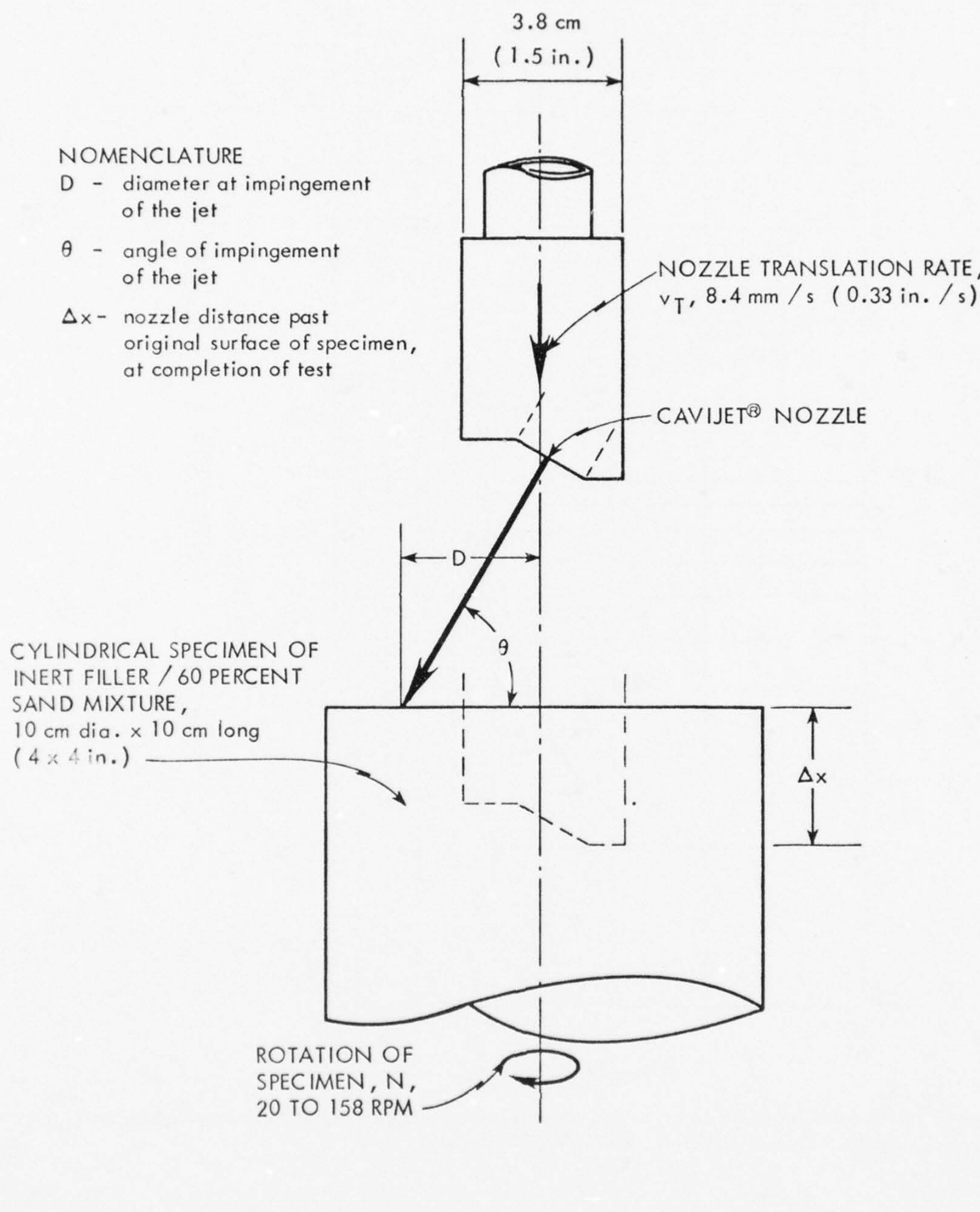


Figure 36 - Configuration for pilot hole testing

Figure 37 - Typical test specimens from pilot hole tests; plain 3.2 mm (0.125 in.) CAVIJET® nozzle, 30° impingement angle, submerged.

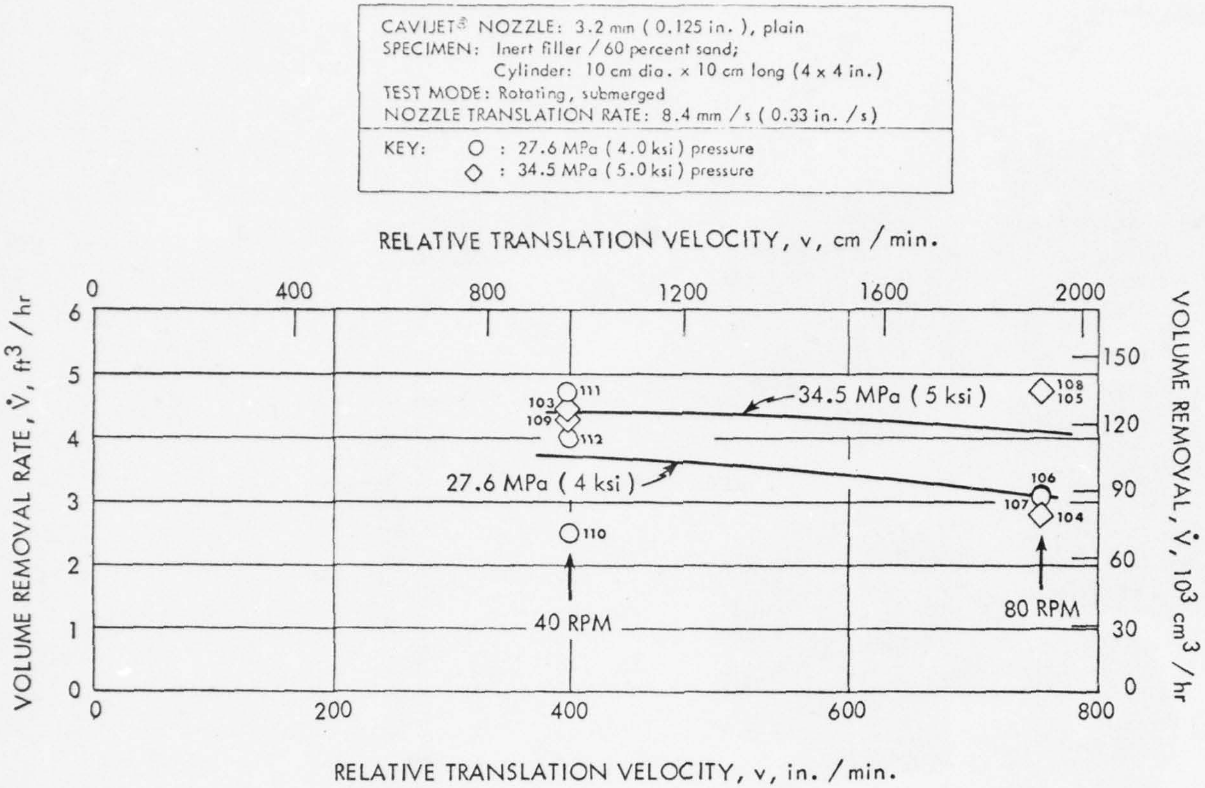


Figure 38 - Effect of relative translation velocity on volume removal rate in pilot hole testing; 30° impingement angle (see Table B-6 for Δx values in each test).

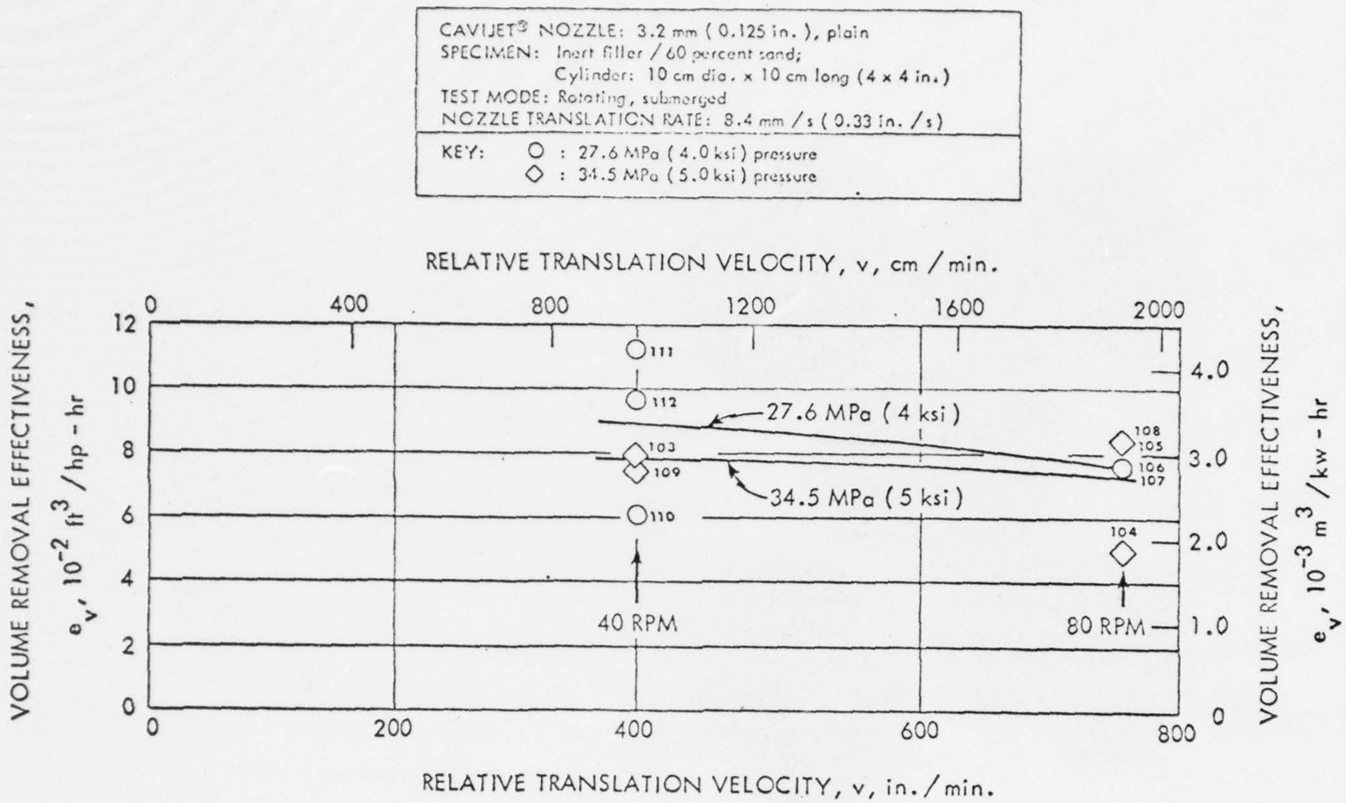


Figure 39 - Effect of relative translation velocity on volume removal effectivess in pilot hole testing; 30° impingement angle.

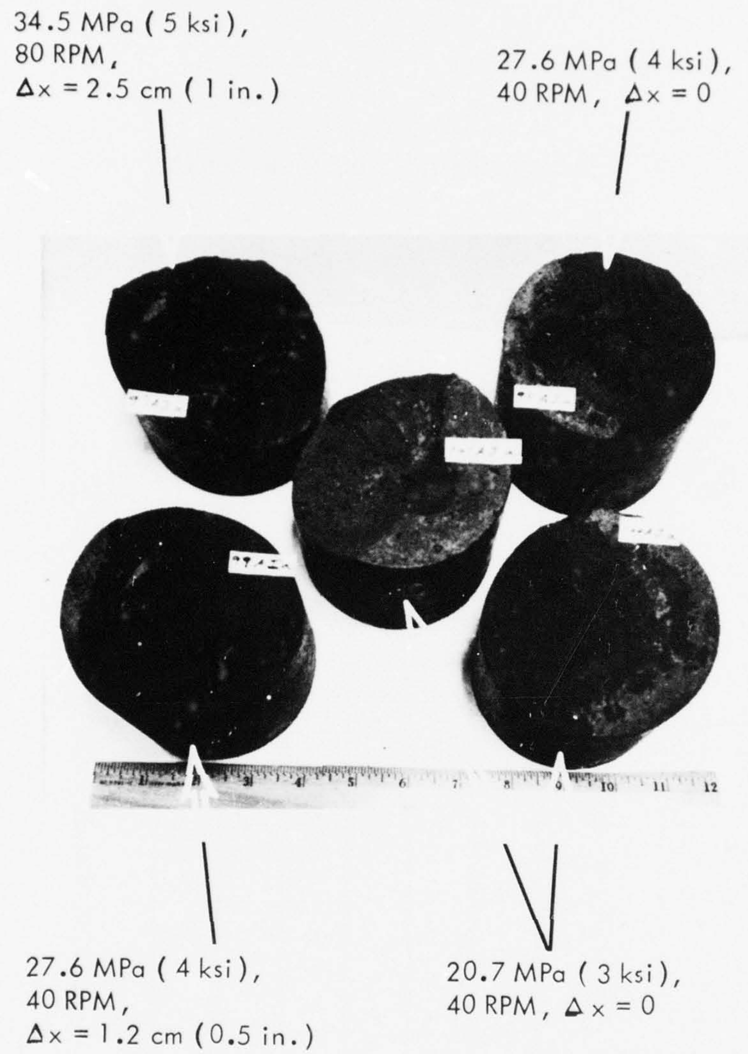


Figure 40 - Typical test specimens from pilot hole tests; plain 3.2 mm (0.125 in.) CAVIJET® nozzle, 45° impingement angle, submerged

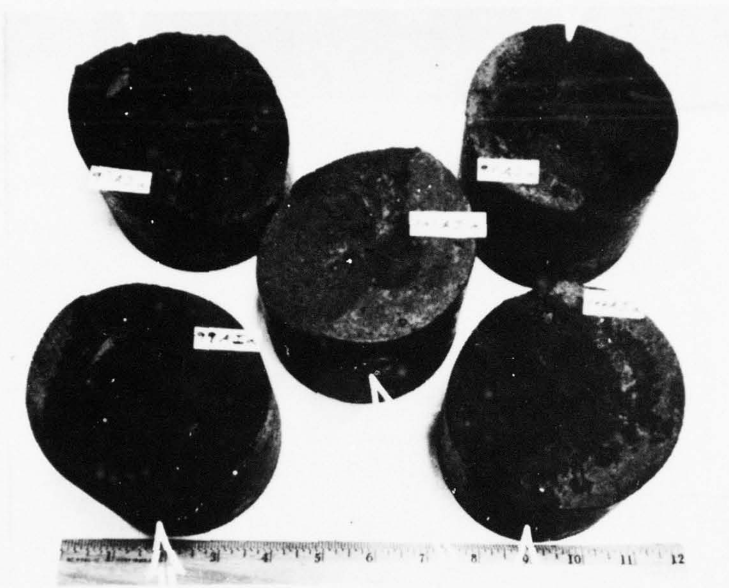


Figure 40 - Typical test specimens from pilot hole tests; plain 3.2 mm (0.125 in.) CAVIJET® nozzle, 45° impingement angle, submerged

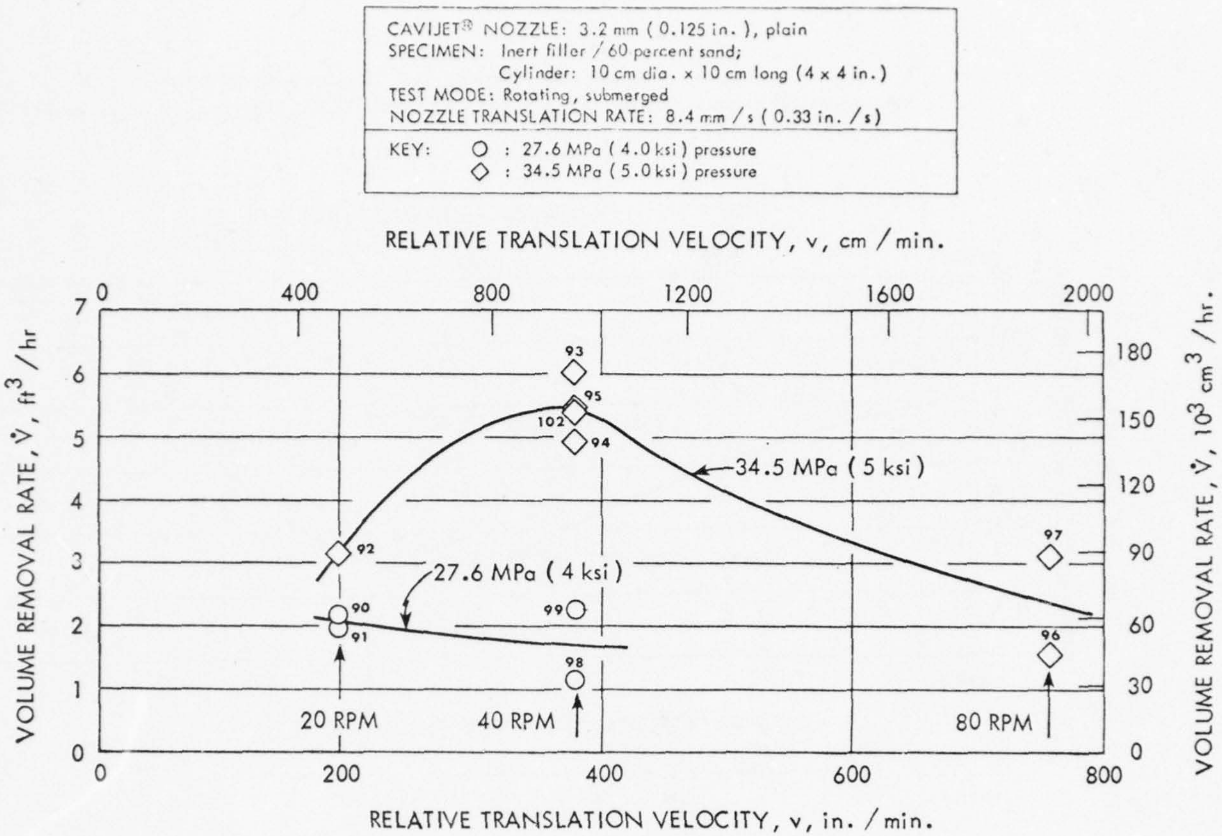


Figure 41 - Effect of relative translation velocity on volume removal rate in in pilot hole testing; 45° impingement angle (see Table B-6 for Δx values in each test).

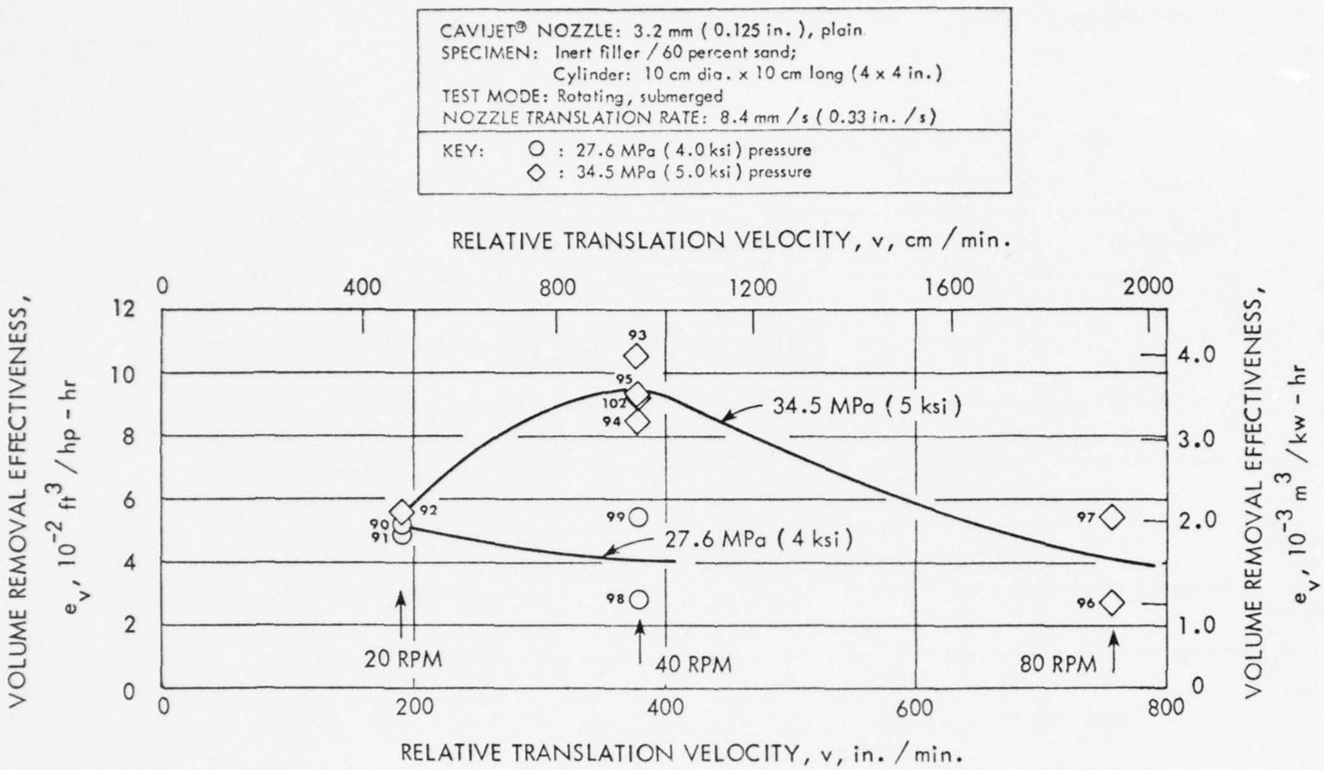


Figure 42 - Effect of relative translation velocity on volume removal effectiveness in pilot hole testing; 45° impingement angle.

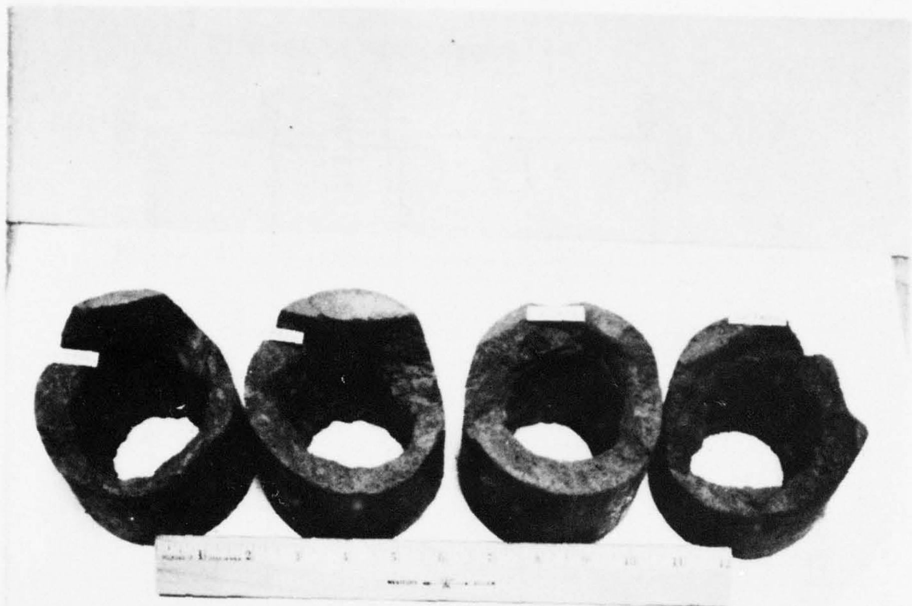


Figure 43 - Typical test specimens from precast fuze hole studies; plain 3.2 mm (0.125 in.) CAVIJET® nozzle, 34.5 MPa (5 ksi). 80 RPM: two specimens at left side; 40 RPM: two specimens at right side of photograph (bottom views: showing broken-off bases of the specimens).

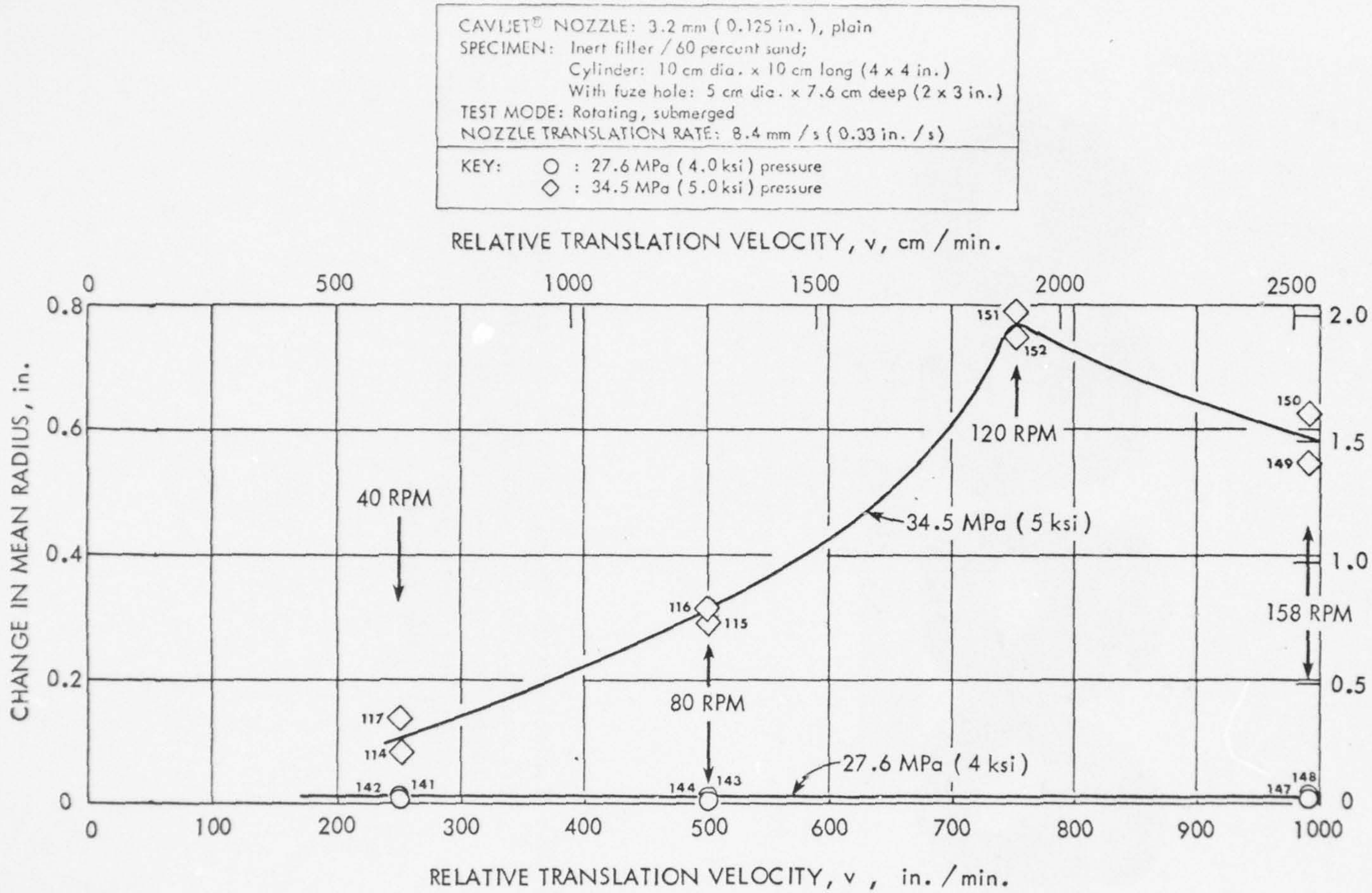


Figure 44 - Effect of relative translation velocity on enlargement of fuze hole radius; 30° impingement angle.

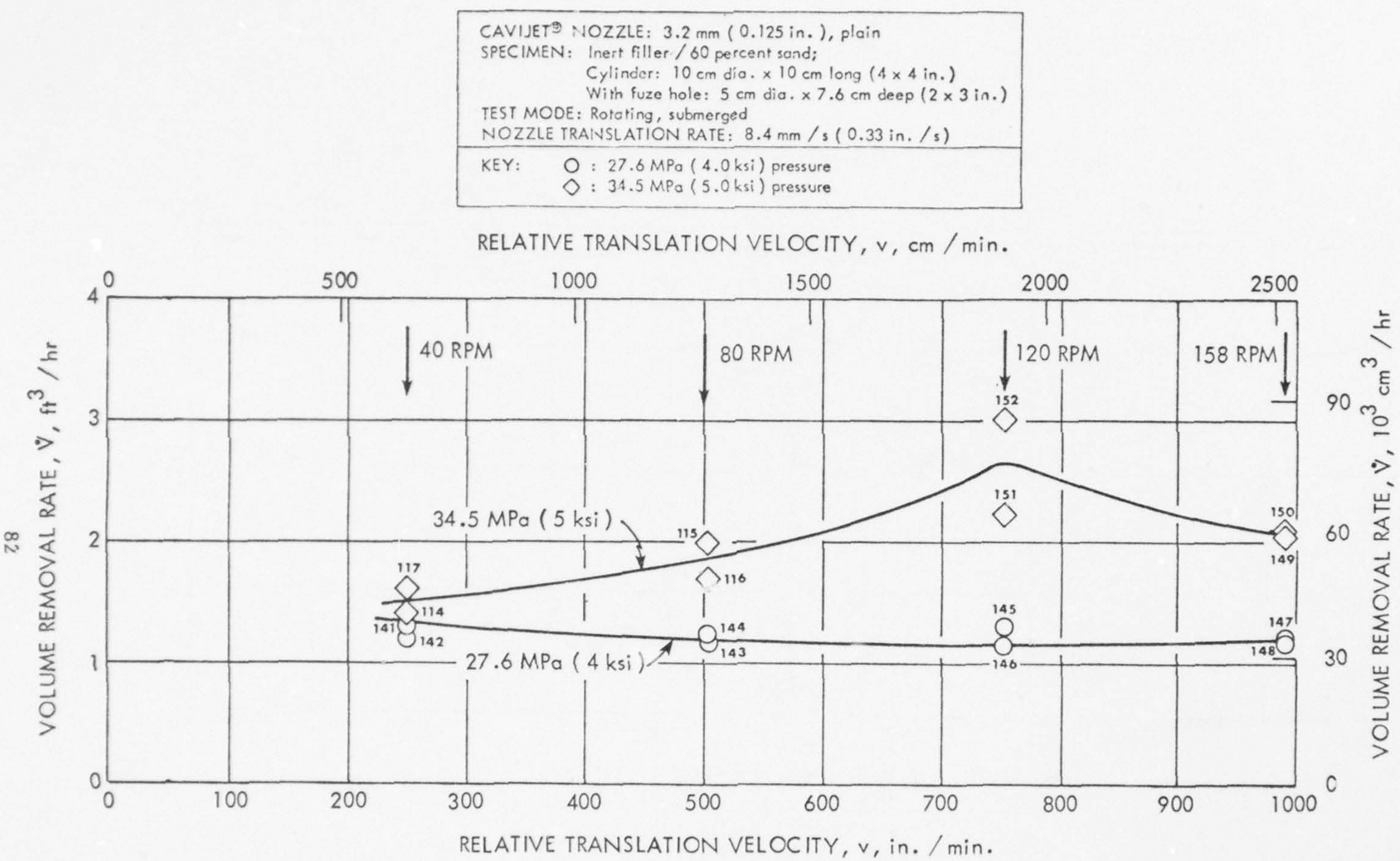


Figure 46 - Effect of relative translation velocity on volume removal rate based on total weight loss; 30° impingement angle.

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REMOVAL OF EXPLOSIVES FROM PROJECTILES USING CAVIJET (TRADE NAM--ETC(U)

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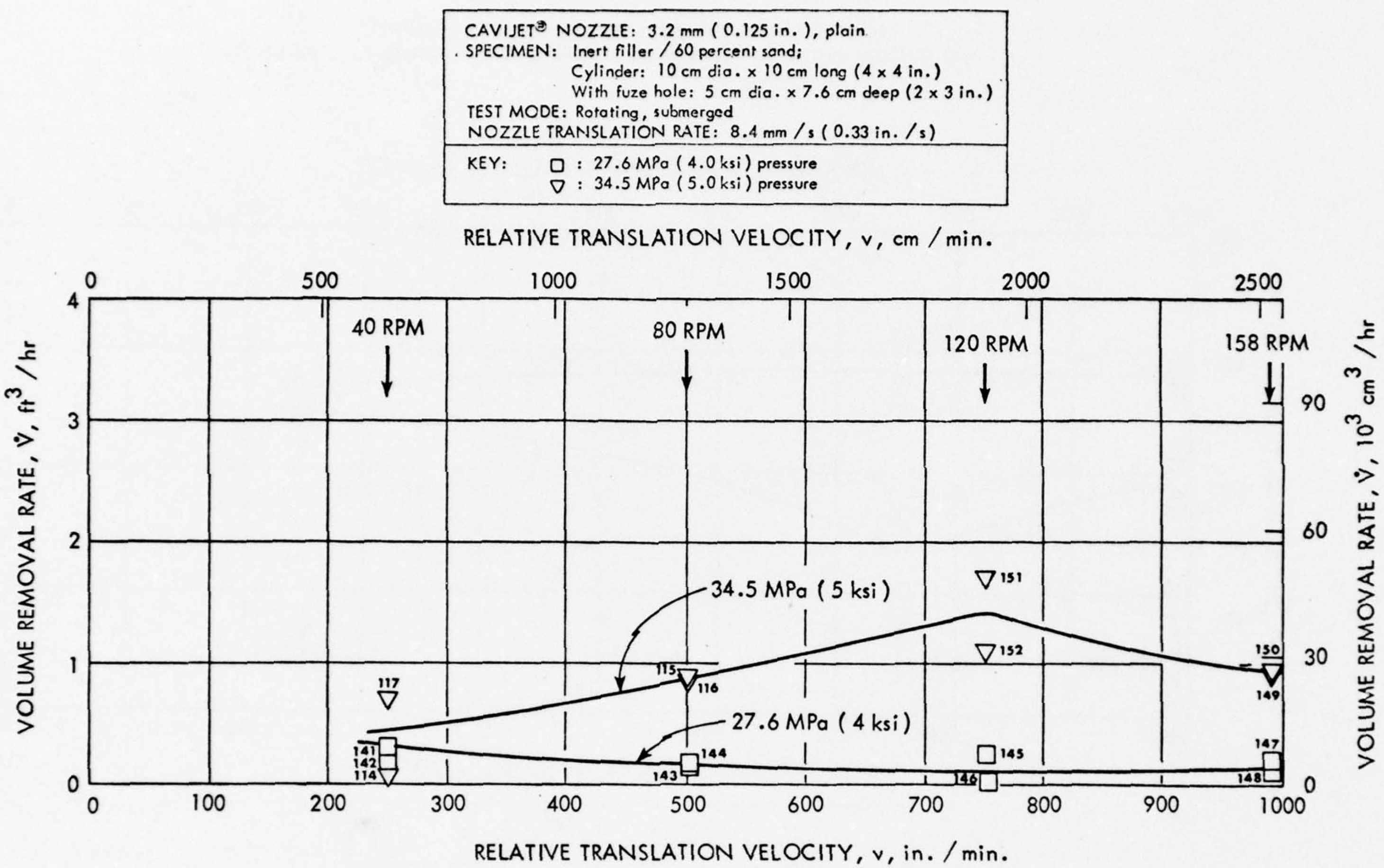


Figure 45 - Effect of relative translation velocity on volume removal rate based on fuze hole erosion; 30° impingement angle.

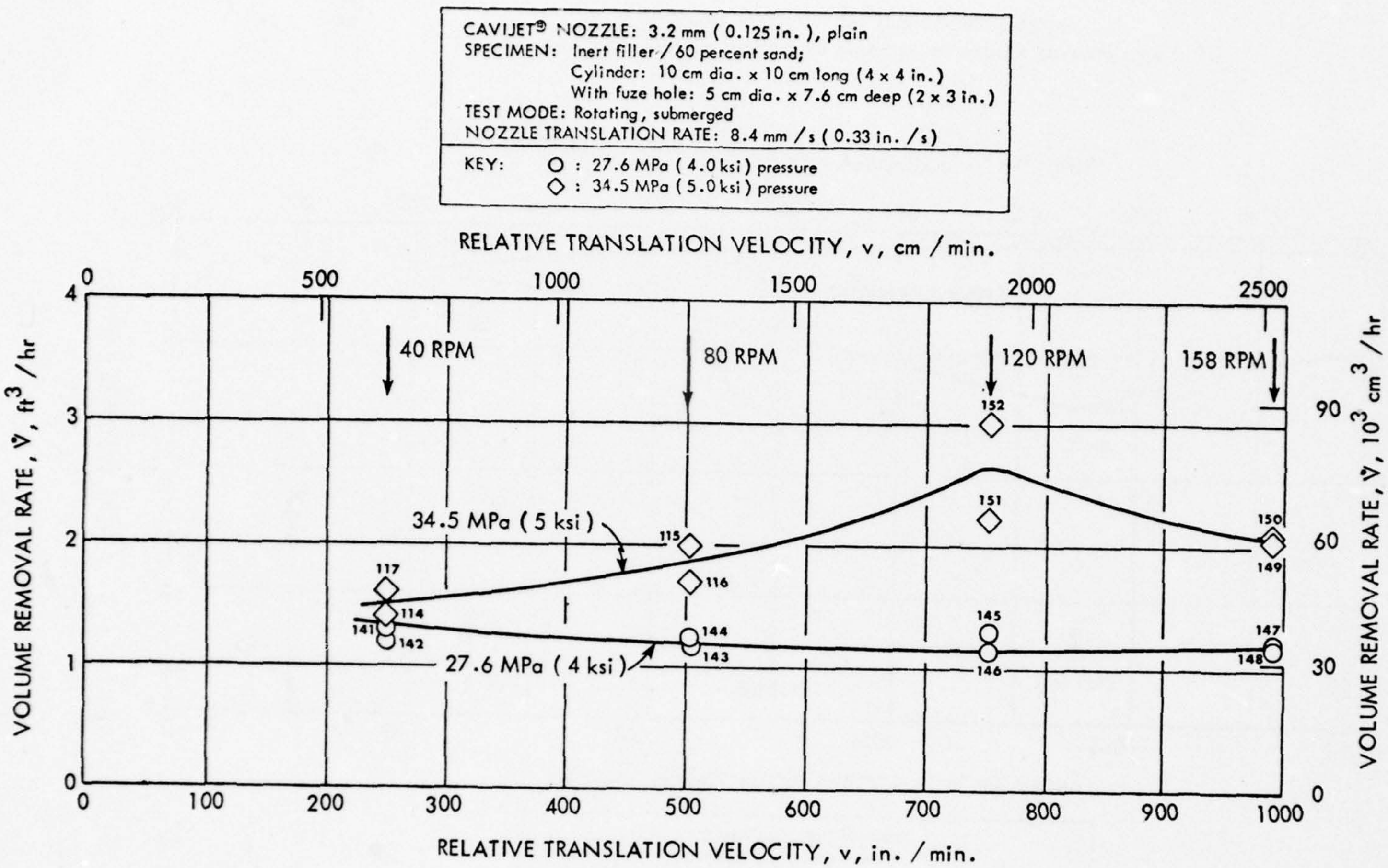


Figure 46 - Effect of relative translation velocity on volume removal rate based on total weight loss; 30° impingement angle.

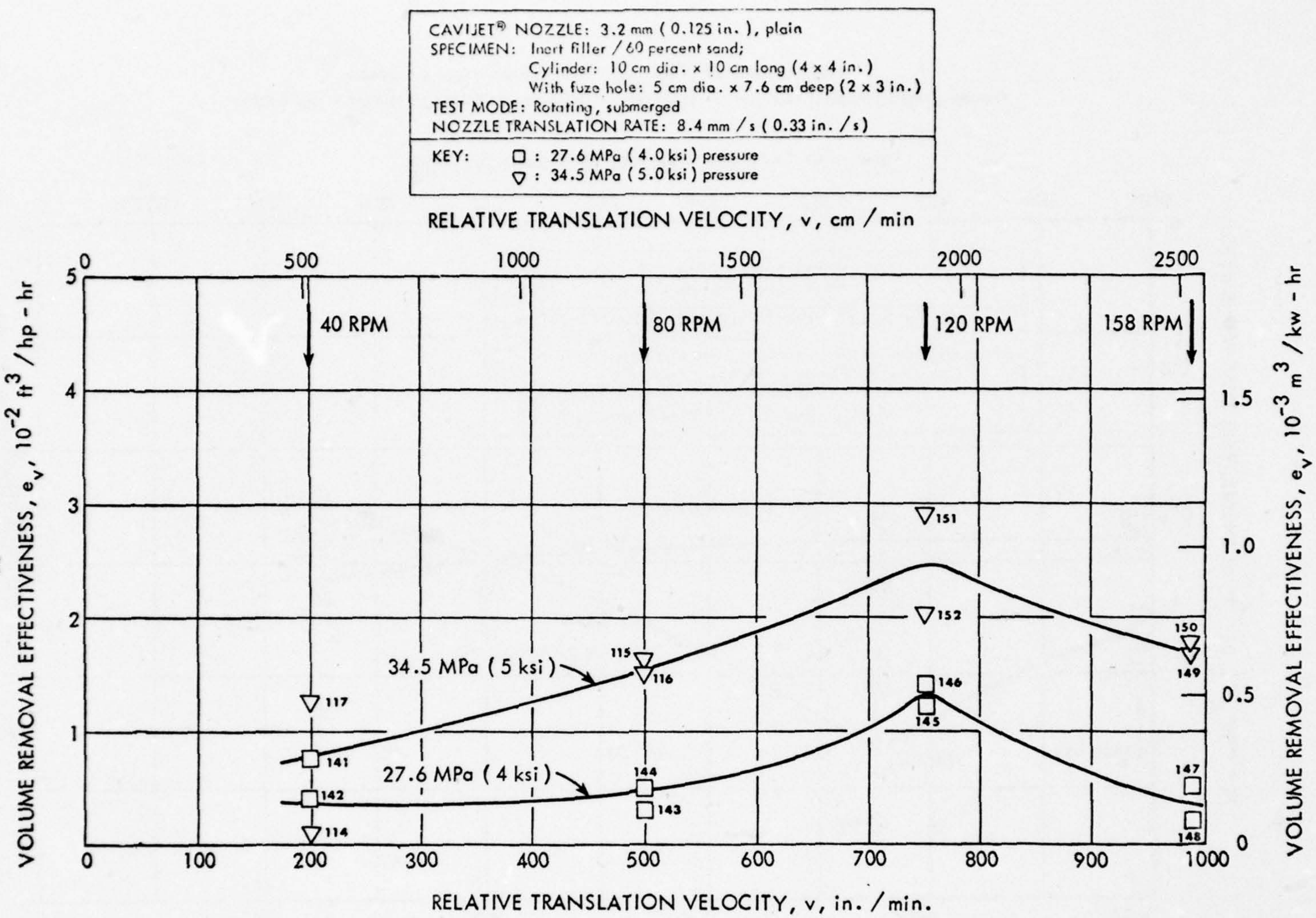


Figure 47 - Effect of relative translation velocity on volume removal effectiveness based on fuze hole erosion; 30° impingement angle.

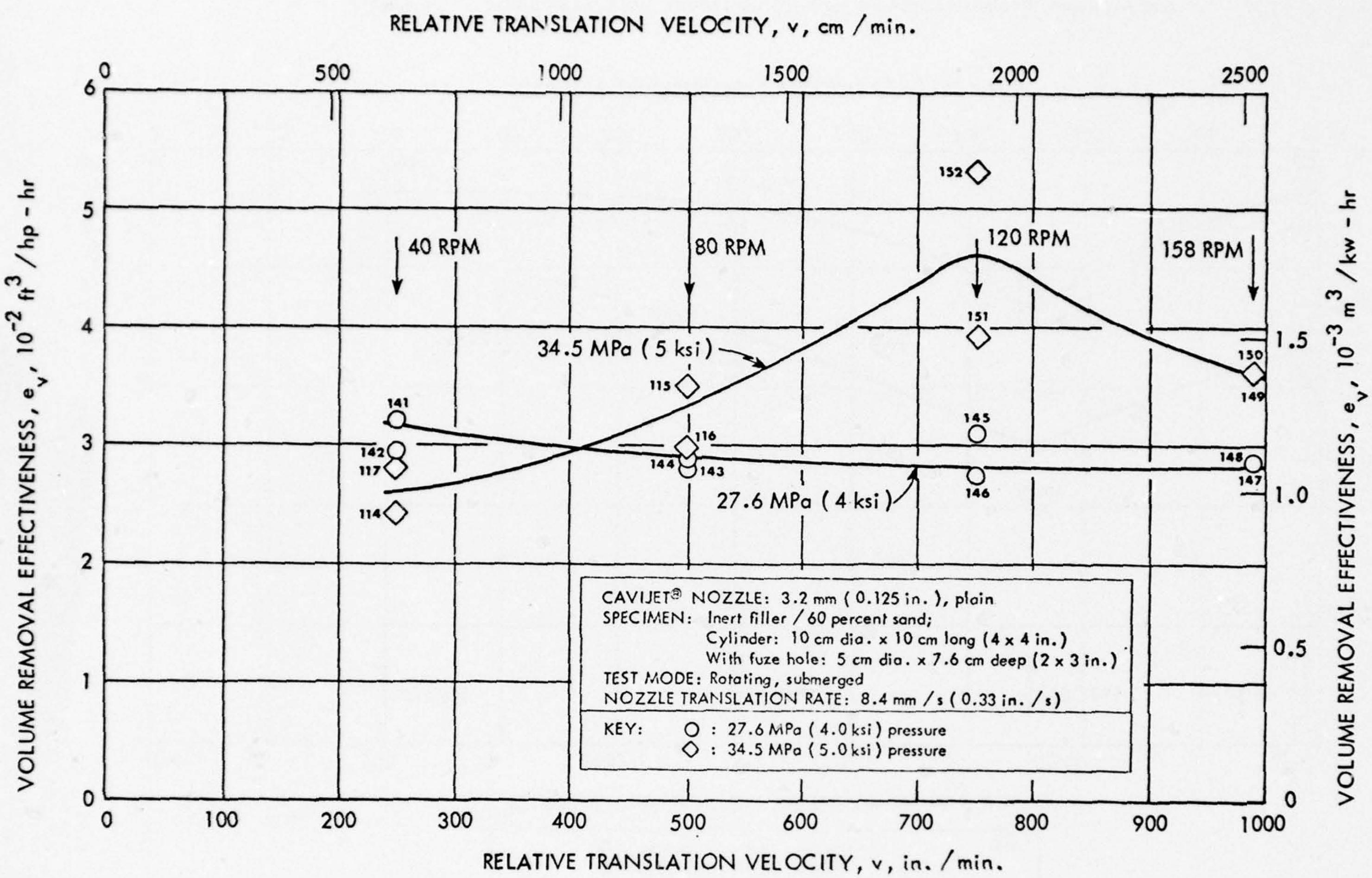


Figure 48 - Effect of relative translation velocity on volume removal effectiveness based on total weight loss; 30° impingement angle.

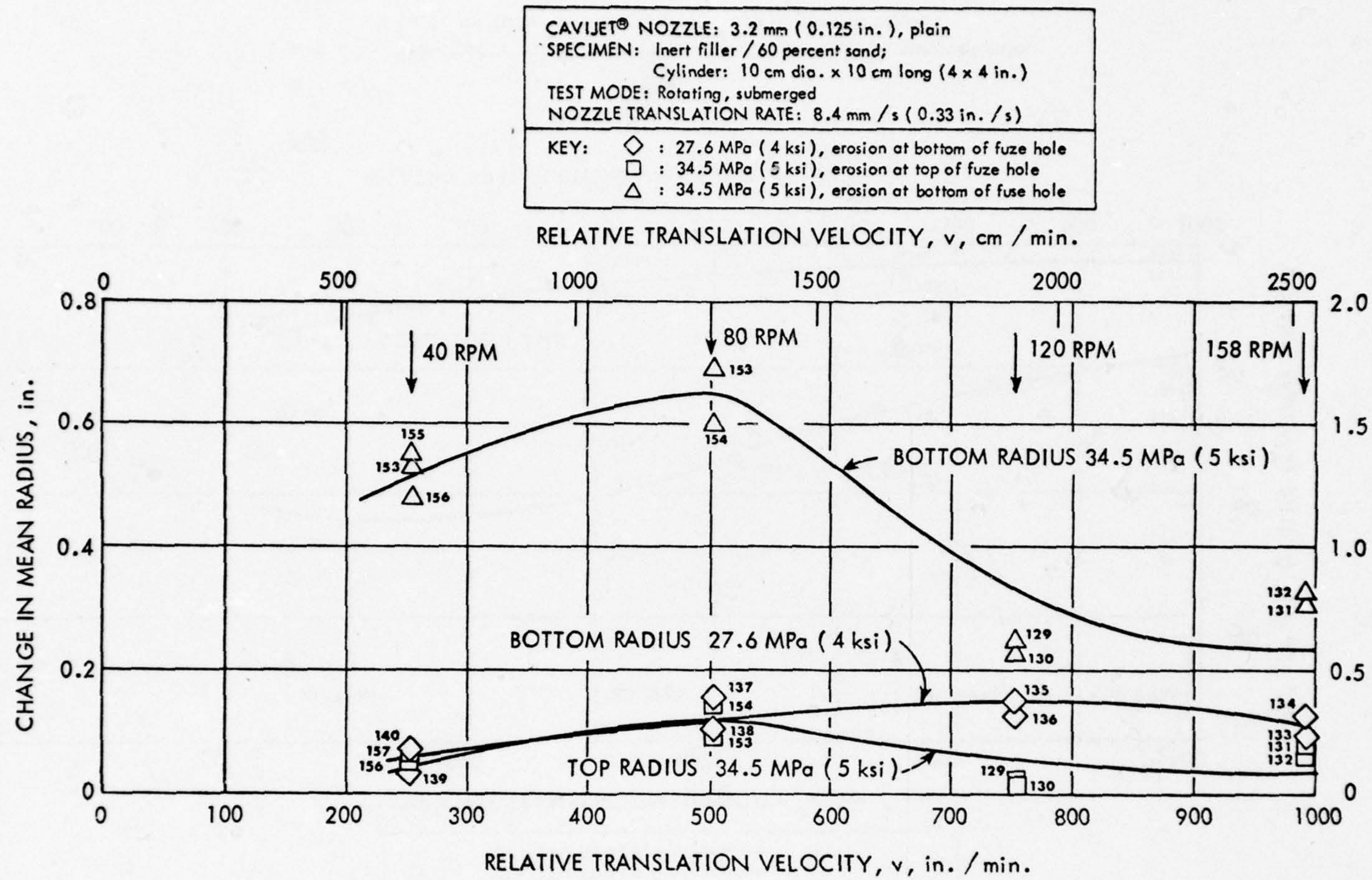


Figure 49 - Effect of relative translation velocity on enlargement of fuze hole radius; 45° impingement angle.

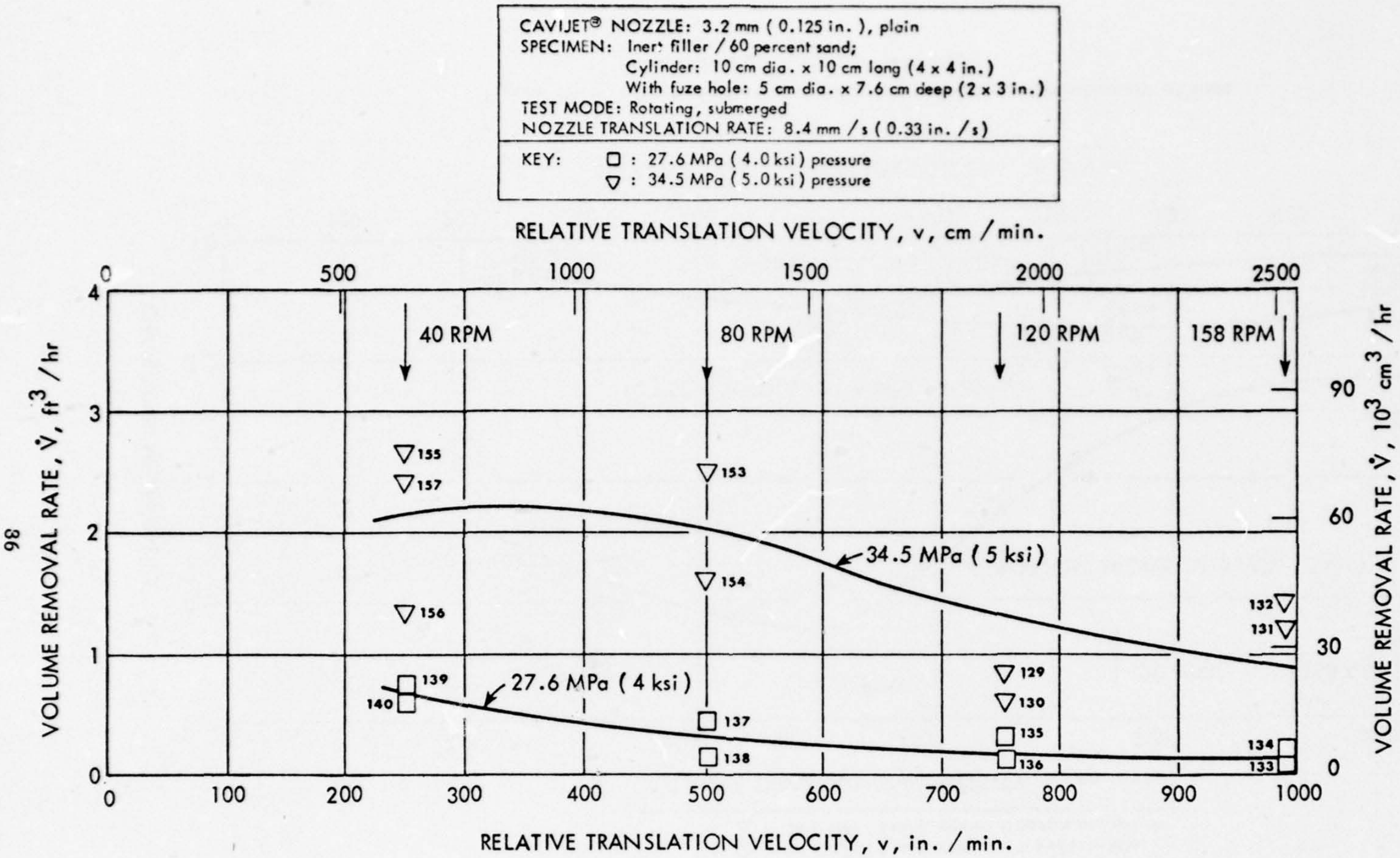


Figure 50 - Effect of relative translation velocity on volume removal rate based on fuze hole erosion; 45° impingement angle.

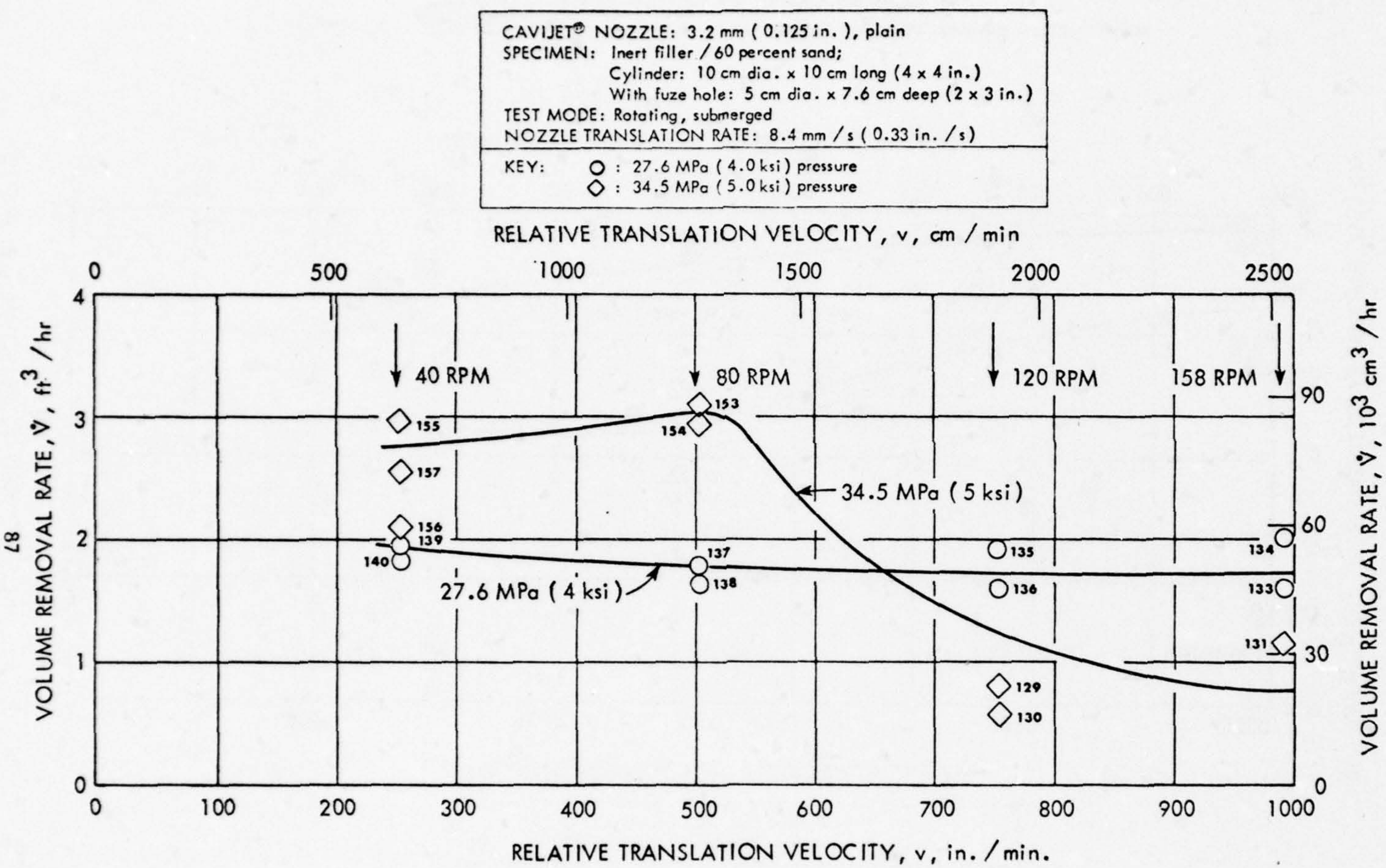


Figure 51 - Effect of relative translation velocity on volume removal rate based on total weight loss; 45° impingement angle.

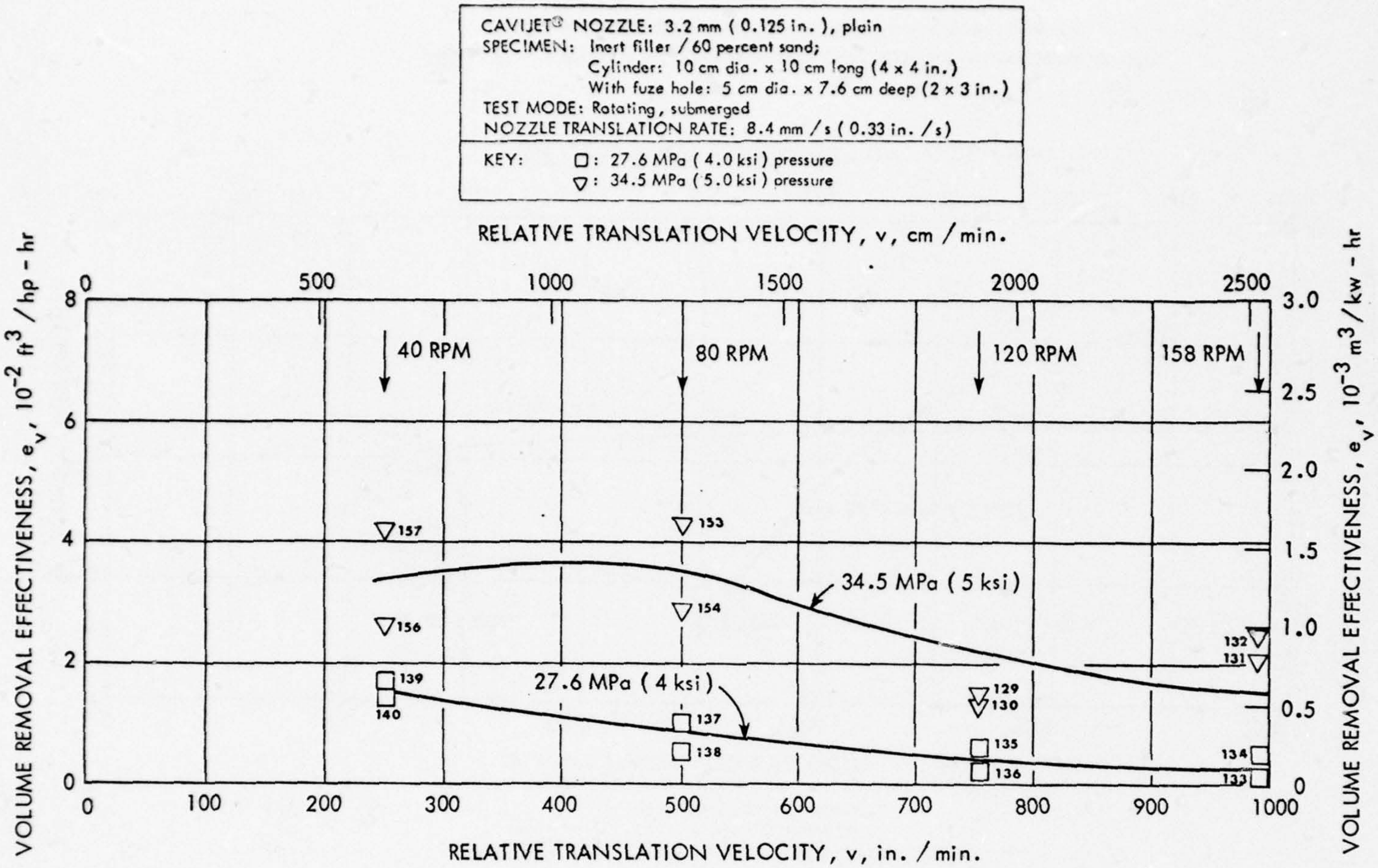


Figure 52 - Effect of relative translation velocity on volume removal effectiveness based on fuze hole erosion; 45° impingement angle.

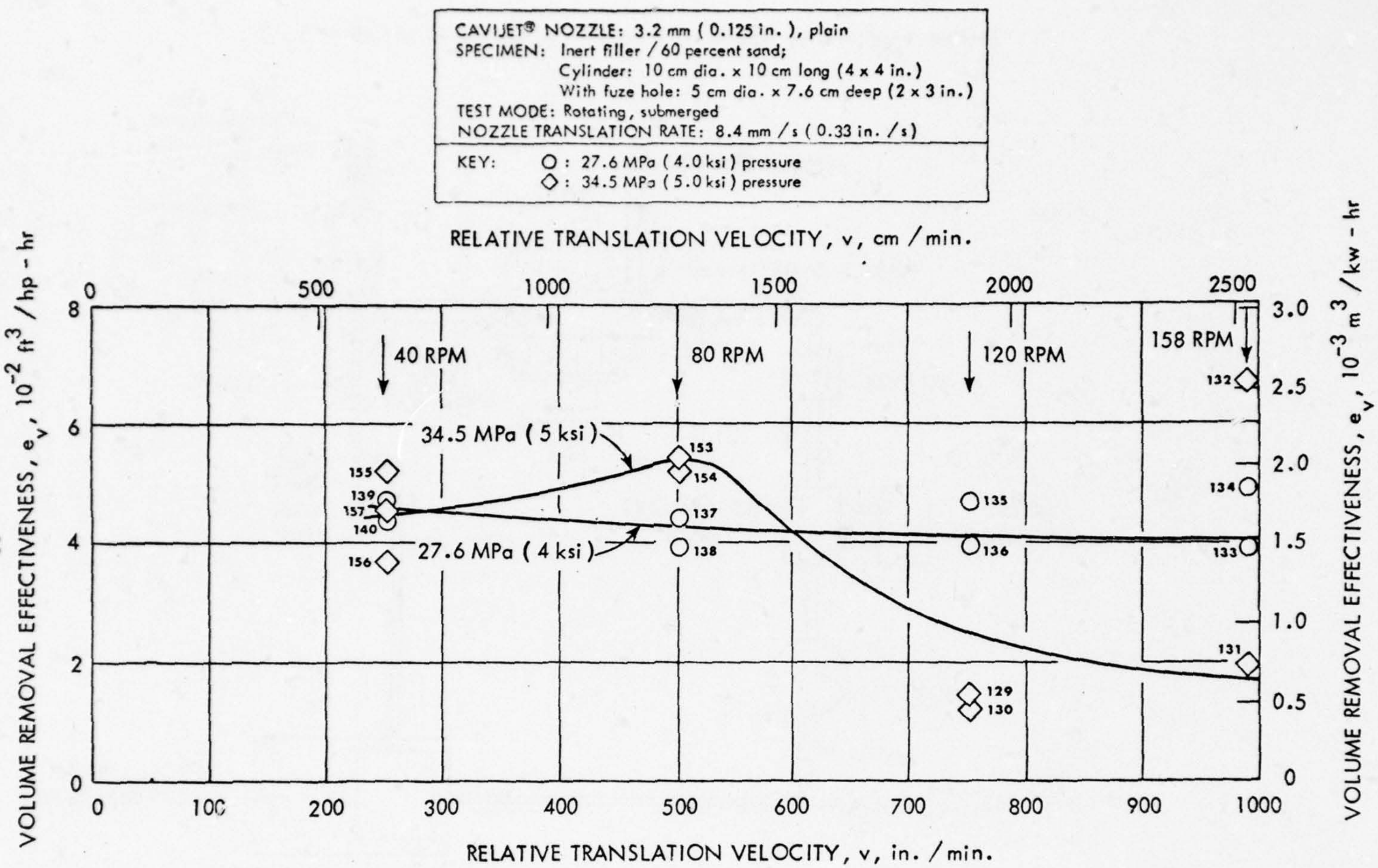


Figure 53 - Effect of relative translation velocity on volume removal effectiveness based on total weight loss; 45° impingement angle.

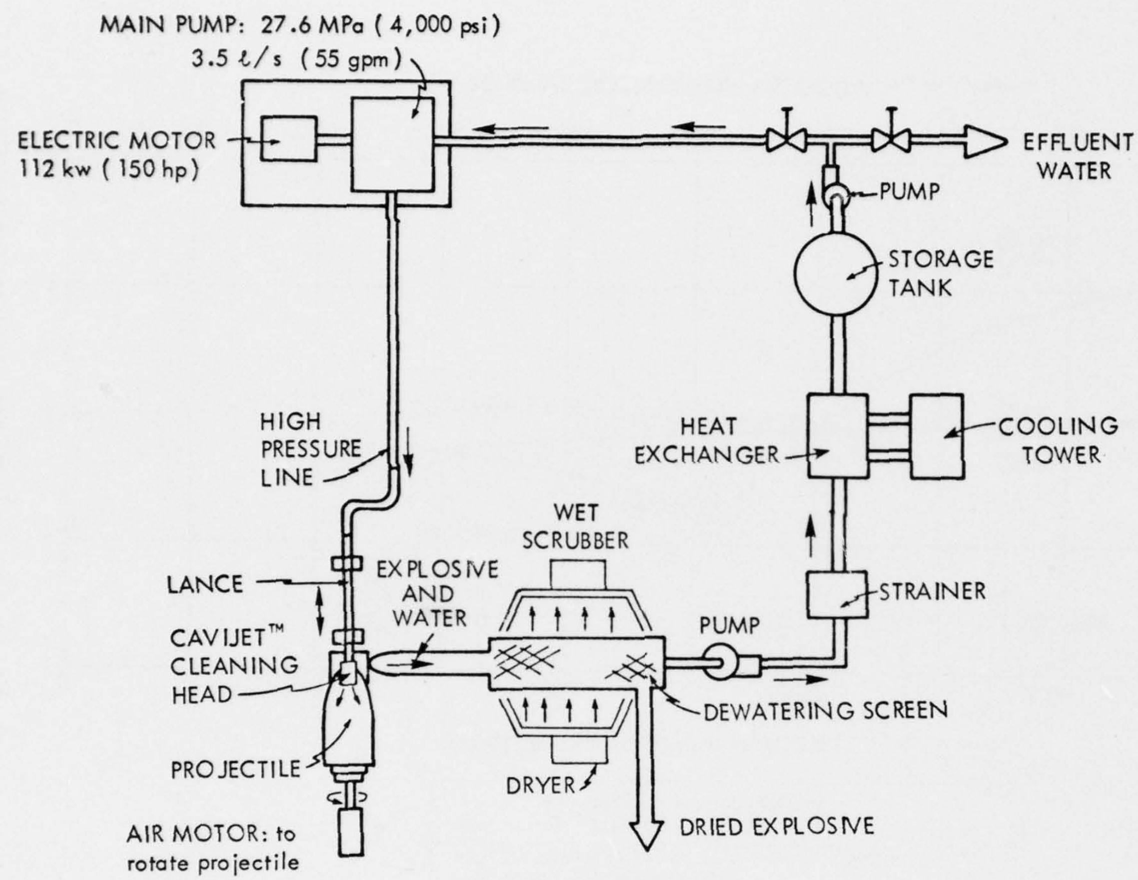
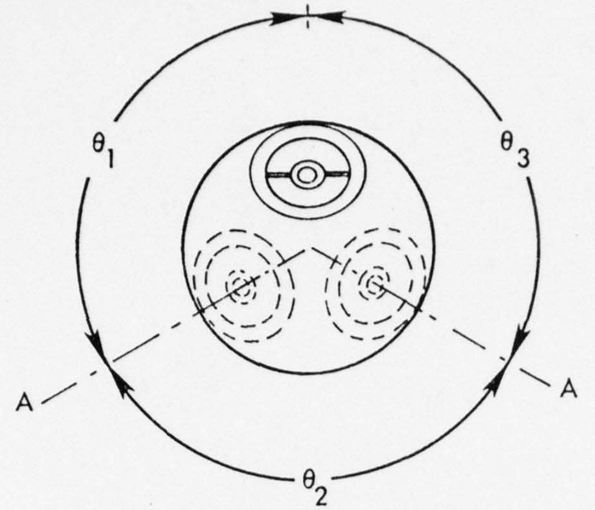
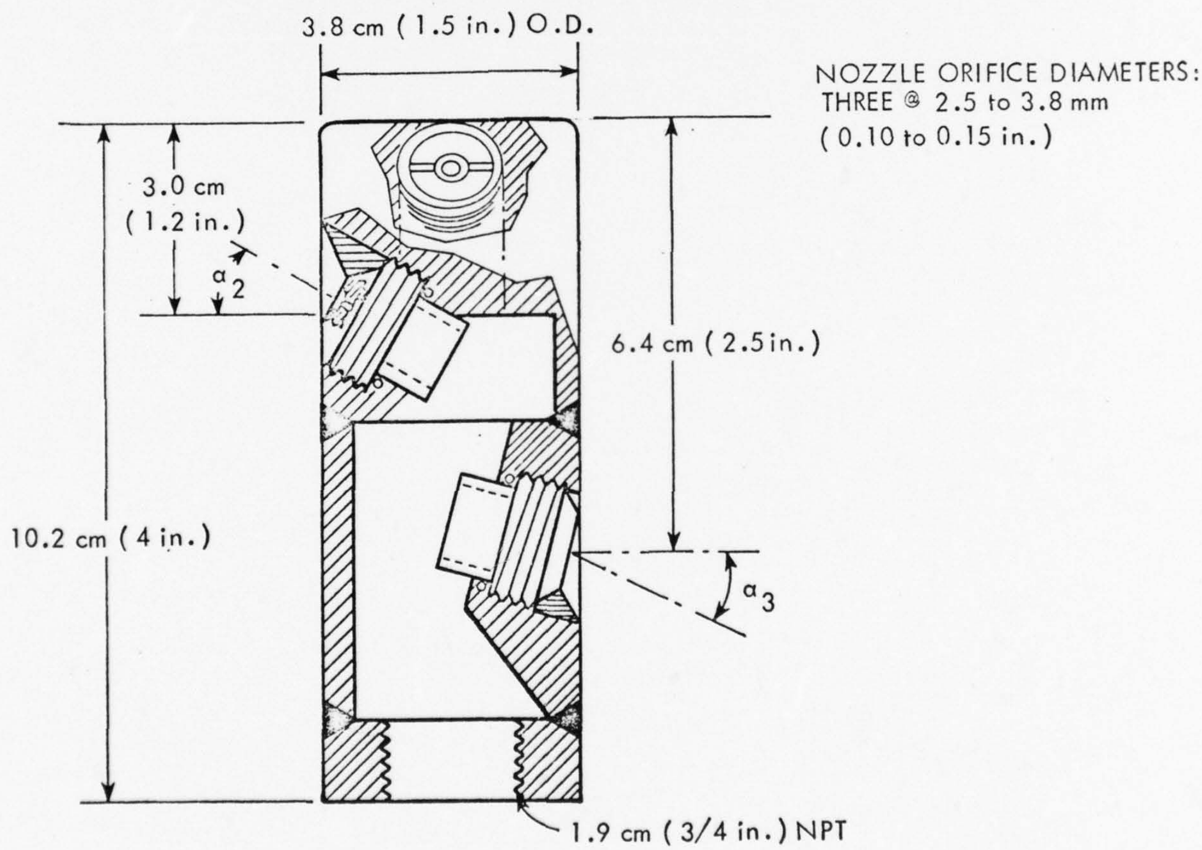


Figure 54 - Pilot CAVIJET® cavitating jet facility for explosive removal.



ANGLE	RANGE (deg.)
α_1 (not shown)	30°- 45°(with respect to ℄ of cleaning head)
α_2	0 - 30°
α_3	0 - 30°
θ_1, θ_2, θ_3 : MUST BE SELECTED, IN CO-ORDINATION WITH α's, TO NULL THE LATERAL THRUST OF THE THREE JETS.	



SECTION A - A

Figure 55 - Preliminary design of CAVIJET® cavitating jet cleaning head for explosive removal

APPENDIX A

SAFETY EVALUATION REPORT:

Prepared by

Hazards Research Corporation

TABLE OF CONTENTS

LIST OF TABLES

I. INTRODUCTION

This report summarizes the results of a series of experiments performed by Hazards Research Corporation, Denville, New Jersey, for Hydronautics, Incorporated, of Laurel, Maryland, under Purchase Order No. 7723.0141-1. Contact with Hydronautics, Incorporated was maintained through Andrew F. Conn, Ph. D.

The objective of this program was to determine experimentally the feasibility of using the CAVIJET cavitating water jet to safely erode Composition B and TNT from stationary test specimens.

II. SUMMARY

An experimental safety evaluation has been performed on the CAVIJET concept for eroding Composition B and TNT from stationary test specimens. A total of 230 tests were performed on 10 cm x 10 cm x 2.5 cm thick TNT and Composition B specimens that were subjected to impingement by a cavitating water jet as it emerged from a nozzle that was operating at either 3, 6 or 10 ksi. Test durations were varied from 20 sec. at 3 ksi to 0.5 sec at 6 ksi to 0.25 sec at 10 ksi. A total of 20.7 minutes of operating time was accumulated without a reaction occurring. A series of 11 tests were performed on two 105 mm projectiles for a total duration of 11 minutes of exposure to the cavitating water jet. No reactions of any kind were observed. The most severe tests on the projectiles were 3 minutes in duration. It was concluded that for the specific conditions tested TNT and Composition B can be safely cut at the 3,000 psi nozzle pressure level. At that pressure, the probability of safety at the 95% confidence level

was 97.4% for Composition B and 95.2% for TNT. It is recommended that 200 additional tests be conducted on 105 mm projectiles at 10 ksi to establish a 98.5% probability of safety at a 95% confidence level.

III. EXPERIMENTAL PROGRAM

A. Materials and Equipment

The following materials and equipment were supplied by Hydronautics for use on this program:

(1) Nylon specimen holders

(2) CAVIJET nozzle with 0.218 cm orifice

(3) CAVIJET nozzle with 0.36 cm orifice

(4) Portable, 10,000 psi capacity, diesel powered, water pump by Weatherford, AAI

(5) High pressure, flexible water hose

(6) Test fixtures for mounting blocks of explosives and 105 mm projectiles

The following materials were supplied by ARRADCOM for use on this program:

(1) TNT blocks, 10 cm x 10 cm x 2.5 cm thick

(2) Composition B blocks, 10 cm x 10 cm x 2.5 cm thick

(3) 105 mm projectiles

B. Description of Experiments

All experiments were performed behind 12 inch thick reinforced concrete walls at HRC's explosive test facility. The diesel operated water pump was positioned outside of the test stand behind one of the walls. A 20 gpm water supply fed the reservoir at the inlet of the pump while a flexible, high pressure hose (10,000 psi capacity) carried the water into the test stand. The hose was connected to a steel pipe

which was mounted vertically on an aluminum angle support structure. The CAVIJET nozzle under evaluation was threaded onto the end of the pipe. Its exit stream was directed downward onto an explosive test specimen.

There were two basic types of explosive test specimens; cast TNT and Comp B blocks and 105 mm projectiles. The test fixture for the cast blocks allowed them to be rigidly held across the 2.54 cm thickness or across the 10 cm x 10 cm length and width. In the former case, the water jet had 10 cm of explosive to erode through while in the latter case the jet impinged on a 2.54 cm thick specimen. In each case a 2.22 cm standoff was used for maximum erosion effectiveness. The test fixture for the 105 mm projectiles consisted of an aluminum cylinder which had four bolts threaded radially toward its center. A 105 mm projectile was placed into this cylinder and held in position by tightening the bolts.

For the explosive block erosion experiments a pneumatically actuated aluminum flapper plate was positioned between the nozzle and the test specimens. A test sequence started with the setting of the test pressure with the flapper plate blocking the water jet. Once the pressure was adjusted, a switch was thrown which simultaneously started an electronic timer and actuated the flapper plate. The plate rotated 90 degrees about a pivot point. This allowed the water jet to impinge on the sample for the desired duration. The test was ended by returning the switch to its original position, thereby causing the

timer to stop and the flapper plate to block the water jet. The pump was disengaged and the sample was removed for examination. A new sample was installed and the cycle was repeated.

For the 105 mm projectile experiments the base of the Nylon specimen holder was removed from its aluminum cylinder support. This support was the fixture which held the 105 mm projectiles. The flapper plate had to be removed for this test series because the CAVIJET nozzle had to be lowered 12.7 cm into the 4.8 cm diameter cavity of the projectile. Therefore, in performing the projectile experiments there was a delay of up to 7 sec. (at 10,000 psi) from actuation of the pump to attainment of full pressure. During this time period the Comp B was exposed to a steadily increasing pressure until the desired steady state pressure was attained.

C. Test Plan

The basic test plan for this program was delineated by ARRADCOM engineering personnel. The specifics of the test plan are as follows:

1. Tests on Cast Explosive Specimens (10 cm x 10 cm x 2.54 cm)

a. TNT

Run 10 samples at 3,000 psi.

Run 10 samples at 6,000 psi.

Run 10 samples at 10,000 psi.

If no reactions occur repeat the above.

If a reaction occurs, stop and institute a sensitivity analysis.

If no reaction occurs after the iteration, (60 samples tested) run 30 samples at 3,000 psi and 10 samples at 10,000 psi.

Balance of samples to be reserved for on site discretionary testing.

Data to be taken: pressure, nozzle size, duration of pulse, orientation of sample, weight of sample before and after jet impingement, approximate size and shape of hole, 35 mm slides of test set-up and of typical blocks.

b. Composition B

Same as TNT above.

2. Tests on 105 mm Projectiles

Two projectiles shall be used as test vehicles. The jet shall be positioned so as to demonstrate the cutting of the explosive without damage to the shell wall. The effect of jet action of 2 to 5 minutes duration on the explosive and on the wall will be assessed.

D. Test Results

1. Tests on Cast Explosive Specimens

Table 1 presents the results of 230 tests performed on Composition B and TNT specimens. There were an equal number of tests performed on each explosive. The first 200 tests were performed in the normal submerged test condition while the last 30 tests were performed in air. One of the observations made

quite early in the program was that the test duration had to be carefully controlled. During the performance of the first 10 trials it was evident that 0.3 sec was a more than adequate duration to erode through a 2.54 cm thick specimen at 10,000 psi. Shorter durations were difficult to achieve since it took about 0.25 sec to cycle the toggle switch (off-on-off). The longest duration tests were performed at 3000 psi for an average of 20 seconds while the 6000 psi tests averaged a maximum of 0.5 sec and the 10,000 psi tests averaged 0.25 seconds.

Once the jet eroded through the test specimen, the test was terminated. Continuation of the run would have been meaningless due to the absence of jet impingement on an explosive surface.

There was no evidence of a reaction of any type on any of the 230 tests performed on this phase of the program. A total of 20.7 minutes of operating time was accumulated without an incident. Water temperature in the test tank did not rise during these tests since fresh water was continually coming into the system. There was no observed difference in erosion characteristics for the 30 tests performed on unsubmerged samples. Nor was there an indication that a reaction of any kind had taken place.

2. Tests on 105 mm Projectiles

Table 2 presents the results of the 11 tests performed on this phase of the program. Two projectiles were subjected to a total

of 11 minutes of exposure to a cavitating water jet. No reactions of any kind were observed. There was no erosion of the steel wall during any of these tests. The most severe tests were 3 minutes in duration. It is anticipated that in actual practice, a projectile would be completely cleaned of Composition B in less than 3 minutes

E. Preliminary Hazards Analysis of CAVIJET

A. Introduction

Careful study of the theoretical operating characteristics of the CAVIJET concept leads to the conclusion that it cannot be analyzed by conventional hazards analysis techniques. Ordinarily, the equipment is analyzed for energy inputs to the explosive under both normal operating conditions and posited abnormal conditions. The result of this analysis is a set of in-process potential data on each process element for the applicable initiation modes. Typical initiation modes analyzed are transient friction, impingement, impact, thermal transition and electrostatic discharge. The calculated in-process potentials are then compared to material response data for the appropriate physical state of the explosive. Material response data is usually available in the literature for materials such as Composition B and TNT. A margin of safety is then calculated as follows:

$$\text{M. S.} = \frac{\text{initiation energy}}{\text{process energy}} - 1$$

The margins of safety allow the engineer to determine the areas in the process where the greatest hazards exist. They provide quantitative proof of the existence or non-existence of in-process potentials capable of initiating the explosives.

There is no clear cut category to place the cavitation phenomena into for the purposes of this analysis. The water jet stream is at a maximum of 10,000 psi in the nozzle but it is amplified at the explosive surface to approximately 100,000 psi. There is an impingement action which is self-cooling. Copious quantities of water are used to erode the explosive. Water flow rates at 3, 6 and 10 ksi pressures are 522, 735 and 944 gms/sec. while erosion rates are roughly 30, 40 and 70 gms/sec. respectively. The water to explosive ratios (wt. basis) are between 13 and 18 to 1.

Currently, propellants and explosives are safely ground in steel hammer mills at water to explosive ratios of 10 to 1. The lack of initiation in the hammer mills is generally attributed to the high cooling rate caused by the water. According to the hot spot theory, the decomposition of explosives is basically a thermal phenomena which results from the dissipation of various kinds of energy in the explosive. This causes a "hot spot" which triggers the decomposition. The high rate of flow of water quenches the "hot spots" before decomposition can begin. It appears, that experience has shown that water to explosive ratios of 10 to 1 provide a safe environment for grinding explosives. It would not be

unreasonable to assume that CAVIJET is analagous to the grinding operation and that it is as safe as the grinding operation.

Hazards analysis requires that the safety aspects of the operation be based on sensitivity data and the establishment of confidence in the calculated results. Therefore, this experimental program was performed in order to:

1. Generate CAVIJET sensitivity data.
2. Determine statistical confidence in the sensitivity data.

B. Discussion

For the purpose of this report, a failure is defined as any ignition of the explosive.

The assumption was made that the probability of a safety failure would increase with an increase in pressure and an increase in duration. Therefore, data obtained from tests conducted at higher pressures was combined with data from tests conducted at lower pressures to determine the safety reliability at the lower pressure.

The following table summarizes the data from the TNT tests:

Summary of TNT Test Results

Pressure (ksi)	Sample Size	Number of Failures	Avg. Dur. (sec)
10	20	0	0.302
6	20	0	0.525
3	20	0	12.040
2	20	0	7.480

The probability of a safe condition for various confidence levels at different pressures is given in the following table:

Probability of a Safe Condition - TNT Tests

Press. (ksi)	Sample Size Used In Probability Calcs.	Lower Confidence Level				
		.50	.80	.90	.95	.99
2	80	.992	.981	.972	.964	.945
3	60	.989	.974	.963	.952	.927
6	40	.983	.921	.945	.928	.892
10	20	.964	.923	.892	.861	.795

The Composition B data is summarized in the following table:

Summary of Composition B Test Results

Pressure (ksi)	Sample Size	Number of Failures	Avg. Dur. (sec)
3	50	0	12.100
6	25	0	0.969
10	35	0	0.320

The probability of a safe condition for various confidence levels at different pressures is given in the following table:

Probability of a Safe Condition - Composition B Tests

Press. (ksi)	Sample Size Used In Probability Calcs.	Lower Confidence Level 0.50	0.80	0.90	0.95	0.99
3	110	.994	.986	.980	.974	.959
6	60	.989	.974	.963	.952	.927
10	35	.981	.956	.937	.918	.877

In addition to the above data, 11 runs were performed on 105 mm projectiles at pressures up to 10,000 psi for up to 3 minute durations without any safety failures. Total duration of these tests was 11 minutes.

IV. CONCLUSIONS

From the results of 230 safety tests conducted on TNT and Composition B test specimens using a 0.218 cm diameter CAVIJET orifice at pressures of 2, 3, 6 and 10 ksi it is possible to conclude the following for the specific conditions tested:

1. No reactions of any type occurred during this test program.
2. TNT and Composition B can be safely cut at the 3,000 psi pressure level.
3. Composition B tests yielded a 97.4% probability of safety at a 95% confidence level for the 3,000 psi tests.

4. TNT tests yielded a 95.2% probability of safety at a 95% confidence level for the 3,000 psi tests.

5. There was no significant difference in erosion characteristics between TNT and Composition B.

For the 11 tests conducted on two 105 mm projectiles it is concluded that no reactions occurred during any of the total of 11 minutes of test time. The CAVIJET appears to be a very effective device for removing explosive from 105 mm projectiles.

V. RECOMMENDATIONS

It is recommended that 200 tests be conducted at 10,000 psi on 105 mm projectiles to establish 98.5% probability of safety at a 95% confidence level. The pressure level of 10,000 psi is 3.3 times the anticipated operational pressure level of 3,000 psi proposed by Hydronautics.

Results of safety tests of the Hydronautics CAVIJET

Test specimens: Composition B and TNT

Sample No.	Mat'l	Thk. (cm)	Weight (gm)		Press. (ksi)	Dur. (sec.)	Result	
			Before	After			Depth	Fracture
1	TNT	2.54	417	315	10	0.32	thru	4 pcs
2	"	"	426	288	"	0.27	thru	5 pcs
3	"	"	432	416	"	0.30	thru	4 pcs
4	"	"	427	350	"	0.28	thru	4 pcs
5	"	"	399	366	"	0.31	thru	3 pcs
6	"	"	436	403	"	0.28	thru	3 pcs
7	"	"	424	385	"	0.32	thru	4 pcs
8	"	"	439	428	"	0.31	thru	3 pcs
9	"	"	402	384	"	0.29	thru	3 pcs
10	"	"	423	300	"	0.28	thru	4 pcs

Note: All tests were conducted using a CAVIJET nozzle with a 0.218 cm orifice and submerged at a 2.22 cm standoff.

Table 1

Results of safety tests of the Hydronautics CAVIJET

Test specimens: Composition B and TNT

Sample No.	Mat'l	Thk. (cm)	Weight (gm)		Press. (ksi)	Dur. (sec.)	Result	
			Before	After			Depth	Fracture
11	TNT	2.54	460	450	6	0.35	thru	1 crack
12	"	"	439	363	"	0.39	thru	3 pcs
13	"	"	452	443	"	0.31	0.95 cm hole, thru	none
14	"	"	352	343	"	0.21	thru	3 pcs
15	"	"	400	392	"	0.27	0.32 cm hole, thru	3 pcs
16	"	"	449	446	"	0.27	0.32 cm hole, thru	2 pcs
17	"	"	373	330	"	0.25	thru	3 pcs
18	"	"	444	428	"	0.30	thru	3 pcs
19	"	"	387	347	"	0.27	thru	3 pcs
20	"	"	407	379	"	0.27	thru	2 pcs

Note: All tests were conducted using a CAVIJET nozzle with a 0.218 cm orifice and submerged at a 2.22 cm standoff.

Results of safety tests of the Hydronautics CAVIJET

Test specimens: Composition B and TNT

Sample No.	Mat'l	Thk. (cm)	Weight (gm) Before	Weight (gm) After	Press. (ksi)	Dur. (sec.)	Result Depth	Result Fracture
21	TNT	2.54	397	378	2	6.96	0.95 cm hole, thru	3 pcs
22	"	"	390	389	"	7.05	0.95 cm hole, 0.5 cm dp.	none
23	"	"	350	325	"	6.96	1.27 cm hole, thru	3 pcs
24	"	"	432	429	"	6.97	0.95 cm hole, 0.5 cm dp.	none
25	"	"	398	383	"	7.05	0.95 cm hole, thru	none
26	"	"	394	359	"	7.02	1.27 cm hole, thru	3 pcs
27	"	"	408	385	"	7.00	0.79 cm hole, thru	2 pcs
28	"	"	393	392	"	6.99	0.95 cm hole, 0.5 cm dp.	none
29	"	"	403	391	"	6.98	0.79 cm hole, thru	3 pcs
30	"	"	389	374	"	7.02	0.32 cm hole, thru	2 pcs

Note: All tests were conducted using a CAVIJET nozzle with a 0.218 cm orifice and submerged at a 2.22 cm standoff.

Table 1

Results of safety tests of the Hydronautics CAVIJET

Test specimens: Composition B and TNT

Sample No.	Mat'l	Thk. (cm)	Weight (gm) Before	Weight (gm) After	Press. (ksi)	Dur. (sec.)	Result Depth	Result Fracture
31	Comp B	2.54	422	410	2	7.28	0.32 cm hole, thru	3 pcs
32	"	"	421	420	"	5.03	0.64 cm hole, 0.32 cm dp.	none
33	"	"	455	453	"	6.99	0.64 cm hole, thru	2 pcs
34	"	"	455	451	2.5	0.98	1.27 cm hole, 0.32 cm dp.	none
35	"	"	454	452	"	5.12	0.64 cm hole, 0.64 cm dp.	none
36	"	"	412	408	"	4.94	0.64 cm hole, 0.95 cm dp.	2 pcs
37	"	"	412	409	"	5.07	0.95 cm hole, 0.95 cm dp.	none
38	"	"	409	388	3	5.05	0.32 cm hole, thru	3 pcs
39	"	"	441	397	"	3.08	thru	3 pcs
40	"	"	460	458	"	0.91	1.27 cm hole, 0.32 cm dp.	none

Note: All tests were conducted using a CAVIJET nozzle with a 0.218 cm orifice and submerged at a 2.22 cm standoff.

Results of safety tests of the Hydronautics CAVIJET

Test specimens: Composition B and TNT

Sample No.	Mat'l	Thk. (cm)	Weight (gm)		Press. (ksi)	Dur. (sec.)	Result	
			Before	After			Depth	Fracture
41	Comp B	2.54	476	451	6	0.26	0.95 cm hole, thru	3 pcs
42	"	"	436	376	"	0.29	0.32 cm hole, thru	4 pcs
43	"	"	466	430	"	0.29	0.95 cm hole, thru	3 pcs
44	"	"	431	403	"	0.33	0.95 cm hole, thru	3 pcs
45	"	"	428	412	"	0.31	0.32 cm hole, thru	3 pcs
46	"	"	452	432	"	0.31	0.32 cm hole, thru	4 pcs
47	"	"	440	334	"	0.19	5 cm dia crater, 0.95 cm dp.	none
48	"	"	408	391	"	0.33	0.95 cm hole, thru	3 pcs
49	"	"	398	387	"	0.30	0.32 cm hole, thru	4 pcs
50	"	"	433	422	"	0.30	0.32 cm hole, thru	3 pcs

Note: All tests were conducted using a CAVIJET nozzle with a 0.218 cm orifice and submerged at a 2.22 cm standoff.

Table 1

Results of safety tests of the Hydronautics CAVIJET

Test specimens: Composition B and TNT

Sample No.	Mat'l	Thk. (cm)	Weight (gm)		Press. (ksi)	Dur. (sec.)	Result	
			Before	After			Depth	Fracture
51	Comp B	2.54	435	308	10	0.26	thru	3 pcs
52	"	"	465	432	"	0.31	1.27 cm hole, thru	4 pcs
53	"	"	435	380	"	0.26	0.32 cm hole, thru	4 pcs
54	"	"	471	461	"	0.31	0.64 cm hole, thru	4 pcs
55	"	"	448	397	"	0.32	1.27 cm hole, thru	3 pcs
56	"	"	432	350	"	0.31	0.64 cm hole, thru	4 pcs
57	"	"	418	235	"	0.30	0.64 cm hole, thru	4 pcs
58	"	"	444	410	"	0.30	0.95 cm hole, thru	3 pcs
59	"	"	449	403	"	0.21	0.95 cm hole, thru	5 pcs
60	"	"	453	422	"	0.23	0.95 cm hole, thru	6 pcs

Note: All tests were conducted using a CAVIJET nozzle with a 0.218 cm orifice and submerged at a 2.22 cm standoff.

Table 1

Results of safety tests of the Hydronautics CAVIJET

Test specimens: Composition B and TNT

Sample No.	Mat'l	Thk. (cm)	Weight (gm) Before	Weight (gm) After	Press. (ksi)	Dur. (sec.)	Result: Depth	Result: Fracture
61	Comp B	10	396	325	3	3.02	5 cm wide, 1.9 cm dp chunk	none
62	"	"	405	343	"	5.00	2.5 cm wide, 2.5 cm dp chunk	3 pcs
63	"	"	426	289	"	9.95	5 cm wide, 3.2 cm dp chunk	3 pcs
64	"	"	493	405	"	20.06	3.2 cm dp.	3 pcs
65	"	"	440	377	"	20.00	0.8 cm hole, 3.8 cm dp.	3 pcs
66	"	"	449	372	"	19.90	0.8 cm hole, 3.8 cm dp.	3 pcs
67	"	"	455	410	"	20.07	could not be measured	2 pcs
68	"	"	407	295	"	20.05	4.5 cm dp.	3 pcs
69	"	"	414	*	"	19.95	could not be measured	only found 2 pcs
70	"	"	438	*	"	20.00	3.2 cm dp.	4 pcs

Note: All tests were conducted using a CAVIJET nozzle with a 0.218 cm orifice and submerged at a 2.22 cm standoff.
*Test specimen broke loose from the holding fixture.

Table 1

Results of safety tests of the Hydronautics CAVIJET

Test specimens: Composition B and TNT

Sample No.	Mat'l	Thk. (cm)	Weight (gm) Before	Weight (gm) After	Press. (ksi)	Dur. (sec.)	Result: Depth	Result: Fracture
71	Comp B	10	441	424	6	0.26	3.8 cm dp.	2 pcs
72	"	"	413	289	"	1.02	5 cm dp.	2 pcs
73	"	"	413	384	"	1.12	0.64 cm hole, 8.3 cm dp.	none
74	"	"	414	*	"	2.02	5 cm dp.	2 pcs
75	"	"	422	*	"	2.03	8.3 cm dp.	4 pcs
76	"	"	423	362	"	3.13	8.3 cm dp.	2 pcs
77	"	"	422	*	"	4.10	specimen shattered into more than 6 pcs	
78	"	"	446	*	"	3.95	6.4 cm dp.	3 pcs
79	"	"	436	393	"	4.00	0.5 cm hole, 9.8 cm dp.	none
80	"	"	456	320	"	4.04	specimen shattered into more than 8 pcs	

Note: All tests were conducted using a CAVIJET nozzle with a 0.218 cm orifice and submerged at a 2.22 cm standoff.

*Test specimen broke loose from the holding fixture.

Table 1

Results of safety tests of the Hydronautics CAVIJET

Test specimens: Composition B and TNT

Sample No.	Mat'l	Thk. (cm)	Weight (gm) Before	Weight (gm) After	Press. (ksi)	Dur. (sec.)	Result: Depth	Result: Fracture
81	Comp B	10	367	359	10	0.26	0.5 cm hole, 3.8 cm dp.	none
82	"	"	420	398	"	0.54	0.5 cm hole, thru	none
83	"	"	445	372	"	0.50	0.95 cm hole, thru	none
84	"	"	457	399	"	0.55	0.5 cm hole, thru	2 pcs
85	"	"	427	372	"	0.48	0.5 cm hole, thru	4 pcs
86	"	"	439	355	"	0.35	0.5 cm hole, thru	none
87	"	"	444	290	"	0.52	thru	3 pcs
88	"	"	423	368	"	0.58	8.3 cm dp.	none
89	"	"	456	405	"	0.53	thru	2 pcs
90	"	"	462	383	"	0.53	0.5 cm hole, thru	8 pcs

Note: All tests were conducted using a CAVIJET nozzle with a 0.218 cm orifice and submerged at a 2.22 cm standoff.

Table 1

Results of safety tests of the Hydronautics CAVIJET

Test specimens: Composition B and TNT

Sample No.	Mat'l	Thk. (cm)	Weight (gm) Before	Weight (gm) After	Press. (ksi)	Dur. (sec.)	Result: Depth	Result: Fracture
91	TNT	10	377	347	10	0.32	0.5 cm hole, 7.6 cm dp.	none
92	"	"	436	403	"	0.29	0.5 cm hole, 7.6 cm dp.	none
93	"	"	382	369	"	0.25	7.6 cm dp.	none
94	"	"	402	281	"	0.57	thru	3 pcs
95	"	"	387	377	"	0.27	6.9 cm dp.	none
96	"	"	373	337	"	0.27	6.4 cm dp.	none
97	"	"	443	395	"	0.25	9.1 cm dp.	none
98	"	"	447	349	"	0.30	thru	2 pcs
99	"	"	411	397	"	0.31	7.6 cm dp.	none
100	"	"	429	398	"	0.25	7.6 cm dp.	none
100A	Inert	"	-	-	"	0.31	7.6 cm dp.	none

Note: All tests were conducted using a CAVIJET nozzle with a 0.218 cm orifice and submerged at a 2.22 cm standoff.

Table 1

Results of safety tests of the Hydronautics CAVIJET

Test specimens: Composition B and TNT

Sample No.	Mat'l	Thk. (cm)	Weight (gm) Before	Weight (gm) After	Press. (ksi)	Dur. (sec.)	Result Depth	Result Fracture
101	TNT	10	472	390	6	1.86	0.6 cm hole, thru	none
102	"	"	463	319	"	1.05	thru	8 pcs
103	"	"	432	404	"	1.03	0.6 cm hole, thru	none
104	"	"	411	354	"	0.51	0.3 cm hole, 7.6 cm dp.	none
105	"	"	471	266	"	0.59	thru	8 pcs
106	"	"	422	373	"	0.47	0.3 cm hole, 8.6 cm dp.	none
107	"	"	432	384	"	0.56	0.3 cm hole, 8.9 cm dp.	none
108	"	"	481	373	"	0.46	thru	3 pcs
109	"	"	457	430	"	0.53	0.3 cm hole, 9.5 cm dp.	none
110	"	"	418	459	"	0.55	thru	4 pcs

Note: All tests were conducted using a CAVIJET nozzle with a 0.218 cm orifice and submerged at a 2.22 cm standoff.

Table 1

Results of safety tests of the Hydronautics CAVIJET

Test specimens: Composition B and TNT

Sample No.	Mat'l	Thk. (cm)	Weight (gm) Before	Weight (gm) After	Press. (ksi)	Dur. (sec.)	Result Depth	Result Fracture
111	TNT	10	472	399	2	3.02	2.5 cm dp.	2 small pcs
112	"	"	470	467	"	4.93	0.64 cm hole, 0.3 cm dp.	none
113	"	"	491	468	"	9.98	1.9 cm dp.	1 small pc
114	"	"	436	356	"	10.07	thru	3 pcs
115	"	"	470	391	"	10.01	3.8 cm dp.	2 chunks off top
116	"	"	425	249	"	10.04	7.6 cm dp.	3 pcs
117	"	"	456	343	"	10.02	3.8 cm dp.	2 chunks off top
118	"	"	428	363	"	20.03	3.8 cm dp.	2 chunks off top
119	"	"	433	376	"	19.87	3.8 cm dp.	top cracked off
120	"	"	459	396	"	20.05	3.5 cm dp.	top cracked off

Note: All tests were conducted using a CAVIJET nozzle with a 0.218 cm orifice and submerged at a 2.22 cm standoff.

Table 1

Results of safety tests of the Hydronautics CAVIJET

Test specimens: Composition B and TNT

Sample No.	Mat'l	Thk. (cm)	Weight (gm)		Press. (ksi)	Dur. (sec.)	Result	
			Before	After			Depth	Fracture
121	TNT	10	436	266	3	3.04	8.3 cm dp.	3 pcs
122	"	"	485	242	"	3.11	5 cm dp.	top cracked off
123	"	"	451	365	"	2.97	thru	5 pcs
124	"	"	402	352	"	3.03	5 cm dp.	top cracked off
125	"	"	422	382	"	3.02	5 cm dp.	none
126	"	"	431	321	"	5.04	5 cm dp.	2 pcs
127	"	"	398	343	"	5.04	5 cm dp.	3 pcs
128	"	"	415	375	"	4.97	5 cm dp.	none
129	"	"	422	362	"	5.01	6.4 cm dp.	none
130	"	"	461	367	"	5.04	4.4 cm dp.	2 pcs

Note: All tests were conducted using a CAVIJET nozzle with a 0.218 cm orifice and submerged at a 2.22 cm standoff.

Table 1

Results of safety tests of the Hydronautics CAVIJET

Test specimens: Composition B and TNT

Sample No.	Mat'l	Thk. (cm)	Weight (gm) Before	Weight (gm) After	Press. (ksi)	Dur. (sec.)	Result Depth	Result Fracture
131	TNT	10	463	354	3	10.04	6.4 cm dp.	intact
132	"	"	444	303	"	10.04	6.4 cm dp.	intact
133	"	"	405	340	"	10.00	7.6 cm dp.	2 pcs
134	"	"	446	*	"	9.97	thru	more than 3 pcs
135	"	"	423	*	"	10.00	thru	1 large and 3 small pcs
136	"	"	418	*	"	20.08	thru	shattered
137	"	"	391	*	"	20.03	thru	many pcs
138	"	"	396	*	"	20.03	thru	shattered
139	"	"	471	328	"	20.00	thru	3 pcs
140	"	"	426	288	"	20.06	thru	3 pcs

Note: All tests were conducted using a CAVIJET nozzle with a 0.218 cm orifice and submerged at a 2.22 cm standoff.

*Test specimen broke loose from the holding fixture.

Table 1

Results of safety tests of the Hydronautics CAVIJET

Test specimens: Composition B and TNT

Sample No.	Mat'l	Thk. (cm)	Weight (gm) Before	Weight (gm) After	Press. (ksi)	Dur. (sec.)	Result Depth	Result Fracture
141	TNT	10	411	312	3	15.05	8.9 cm dp.	2 pcs
142	"	"	367	265	"	15.06	8.9 cm dp.	3 pcs
143	"	"	438	359	"	.14.97	7 cm dp.	3 pcs
144	"	"	377	*	"	15.05	thru	shattered
145	"	"	460	298	"	14.50	8.9 cm dp.	2 pcs
146	"	"	410	325	"	14.94	5 cm dp.	2 pcs
147	"	"	431	173	"	15.07	thru	shattered
148	"	"	414	364	"	14.95	5 cm dp.	3 pcs
149	"	"	385	251	"	15.00	8.9 cm dp.	2 pcs
150	"	"	468	337	"	15.12	thru	4 pcs

Note: All tests were conducted using a CAVIJET nozzle with a 0.218 cm orifice and submerged at a 2.22 cm standoff.
*Test specimen broke loose from the holding fixture.

Table 1

Results of safety tests of the Hydronautics CAVIJET

Test specimens: Composition B and TNT

Sample No.	Mat'l	Thk. (cm)	Weight (gm) Before	Weight (gm) After	Press. (ksi)	Dur. (sec.)	Result Depth	Result Fracture
. 151	Comp B	10	451	394	3	2.98	5 cm dp.	3 pcs
152	"	"	437	388	"	3.05	5 cm dp.	intact
153	"	"	446	352	"	3.01	3.8 cm dp.	eroded top
154	"	"	449	387	"	3.00	3.8 cm dp.	eroded top
155	"	"	466	408	"	2.96	2.5 cm dp.	eroded top
156	"	"	499	467	"	5.05	4.4 cm dp.	2 pcs
157	"	"	472	457	"	5.02	3.2 cm dp.	2 pcs
158	"	"	439	369	"	5.01	4.4 cm dp.	intact
159	"	"	465	453	"	5.03	3.5 cm dp.	intact
160	"	"	443	405	"	4.96	5 cm dp.	2 pcs

Note: All tests were conducted using a CAVIJET nozzle with a 0.218 cm orifice and submerged at a 2.22 cm standoff.

Table 1

Results of safety tests of the Hydronautics CAVIJET

Test specimens: Composition B and TNT

Sample No.	Mat'l	Thk. (cm)	Weight (gm) Before	Weight (gm) After	Press. (ksi)	Dur. (sec.)	Result Depth	Result Fracture
161	Comp B	10	457	352	3	10.05	5 cm dp.	3 pcs
162	"	"	431	379	"	10.06	5 cm dp.	2 pcs
163	"	"	460	382	"	10.04	7.6 cm dp.	2 pcs
164	"	"	453	370	"	10.03	5 cm dp.	4 pcs
165	"	"	461	426	"	10.01	3 cm dp.	3 pcs
166	"	"	424	367	"	20.02	5 cm dp.	3 pcs
167	"	"	462	400	"	19.98	7.6 cm dp.	3 pcs
168	"	"	432	315	"	20.04	5 cm dp.	4 pcs
169	"	"	462	322	"	19.98	6.4 cm dp.	5 pcs
170	"	"	490	450	"	19.99	6.4 cm dp.	2 pcs

Note: All tests were conducted using a CAVIJET nozzle with a 0.218 cm orifice and submerged at a 2.22 cm standoff.

Table 1

Results of safety tests of the Hydronautics CAVIJET

Test specimens: Composition B and TNT

Sample No.	Mat'l	Thk. (cm)	Weight (gm)		Press. (ksi)	Dur. (sec.)	Result	
			Before	After			Depth	Fracture
171	Comp B	10	447	350	3	31.04	6.4 cm dp.	2 pcs
172	"	"	398	*	"	30.05	5 cm dp.	3 pcs
173	"	"	464	*	"	30.04	thru	shattered
174	"	"	434	274	"	30.03	4.4 cm dp.	3 pcs
175	"	"	431	*	"	30.04	thru	shattered
176	"	"	482	377	"	15.00	5 cm dp.	3 pcs
177	"	"	440	371	"	15.04	5 cm dp.	2 pcs
178	"	"	425	240	"	15.04	could not be measured	3 pcs
179	"	"	455	348	"	15.03	5 cm dp.	3 pcs
180	"	"	415	322	"	15.04	5 cm dp.	2 pcs

Note: All tests were conducted using a CAVIJET nozzle with a 0.218 cm orifice and submerged at a 2.22 cm standoff.
*Test specimen broke loose from the holding fixture.

Table 1

Results of safety tests of the Hydronautics CAVIJET

Test specimens: Composition B and TNT

Sample No.	Mat'l	Thk. (cm)	Weight (gm) Before	Weight (gm) After	Press. (ksi)	Dur. (sec.)	Result Depth	Result Fracture
181	Comp B	10	446	427	10	0.28	0.3 cm hole, 7.6 cm dp.	intact
182	"	"	490	397	"	0.25	7.6 cm dp.	3 pcs
183	"	"	447	363	"	0.35	7.6 cm dp.	2 pcs
184	"	"	444	391	"	0.22	7 cm dp.	4 pcs
185	"	"	465	360	"	0.28	6.4 cm dp.	2 pcs
186	"	"	447	430	"	0.27	7.3 cm dp.	intact
187	"	"	475	445	"	0.28	6.4 cm dp.	2 pcs
188	"	"	454	395	"	0.34	5.7 cm dp.	3 pcs
189	"	"	413	396	"	0.24	7.6 cm dp.	intact
190	"	"	461	*	"	0.25	could not be measured	4 pcs

Note: All tests were conducted using a CAVIJET nozzle with a 0.218 cm orifice and submerged at a 2.22 cm standoff.

*Test specimen broke loose from the holding fixture.

Table 1

Results of safety tests of the Hydronautics CAVIJET

Test specimens: Composition B and TNT

Sample No.	Mat'l	Thk. (cm)	Weight (gm) Before	After	Press. (ksi)	Dur. (sec.)	Result Depth	Fracture
191	TNT	10	451	277	10	0.29	7 cm dp.	2 pcs
192	"	"	446	430	"	0.26	9.2 cm dp.	intact
193	"	"	444	436	"	0.29	8.6 cm dp.	intact
194	"	"	401	320	"	0.25	9.2 cm dp.	4 pcs
195	"	"	406	377	"	0.26	7.6 cm dp.	intact
196	"	"	425	385	"	0.31	0.32 cm hole, 10 cm dp.	intact
197	"	"	468	439	"	0.23	0.64 cm hole, 10 cm dp.	intact
198	"	"	454	355	"	0.28	10 cm dp.	4 pcs
199	"	"	439	426	"	0.23	7.3 cm dp.	intact
200	"	"	421	310	"	0.28	8.9 cm dp.	6 pcs

Note: All tests were conducted using a CAVIJET nozzle with a 0.218 cm orifice and submerged at a 2.22 cm standoff.

Table 1

Results of safety tests of the Hydronautics CAVIJET

Test specimens: Composition B and TNT

Sample No.	Mat'l	Thk. (cm)	Weight (gm) Before	Weight (gm) After	Press. (ksi)	Dur. (sec.)	Result Depth	Result Fracture
201[a]	TNT	10	426	370	10	0.31	thru	intact
202[a]	"	"	443	350	"	0.26	thru	3 pcs
203[a]	"	"	430	320	"	0.28	thru	intact
204[a]	"	"	481	439	"	0.23	thru	intact
205[a]	"	"	467	380	"	0.35	thru	intact
206[a]	"	"	429	417	6	0.27	6.4 cm dp.	intact
207[a]	"	"	420	245	"	0.54	thru	3 pcs
208[a]	"	"	442	368	"	0.55	thru	intact
209[a]	"	"	443	420	"	0.54	8.9 cm dp.	intact
210[a]	"	"	426	398	"	0.52	9.5 cm dp.	intact

Note: All tests were conducted using a CAVIJET nozzle with a 0.218 cm orifice at a 2.22 cm standoff.

[a]These samples were tested in air.

Table 1

Results of safety tests of the Hydronautics CAVIJET

Test specimens: Composition B and TNT

Sample No.	Mat'l	Thk. (cm)	Weight (gm)		Press. (ksi)	Dur. (sec.)	Result	
			Before	After			Depth	Fracture
211[a]	TNT	10	428	380	3	2.95	7 cm dp.	intact
212[a]	"	"	397	344	"	2.98	thru	intact
213[a]	"	"	403	290	"	3.00	9.5 cm dp.	intact
214[a]	"	"	477	429	"	3.01	8.3 cm dp.	3 pcs
215[a]	"	"	414	378	"	2.91	9.5 cm dp.	intact
216[a]	Comp B	10	515	288	10	0.38	thru	intact
217[a]	"	"	467	360	"	0.23	thru	intact
218[a]	"	"	465	403	"	0.29	thru	intact
219[a]	"	"	476	458	"	0.27	9.5 cm dp.	intact
220[a]	"	"	457	435	"	0.22	8.9 cm dp.	intact

Note: All tests were conducted using a CAVIJET nozzle with a 0.218 cm orifice at a 2.22 cm standoff.
[a]These samples were tested in air.

Table 1

Results of safety tests of the Hydronautics CAVIJET

Test specimens: Composition B and TNT

Sample No.	Mat'l	Thk. (cm)	Weight (gm) Before	Weight (gm) After	Press. (ksi)	Dur. (sec.)	Result Depth	Result Fracture
221[a]	Comp B	10	498	460	6	0.58	9.1 cm dp.	intact
222[a]	"	"	479	420	"	0.52	thru	intact
223[a]	"	"	420	386	"	0.53	8.5 cm dp.	intact
224[a]	"	"	476	462	"	0.50	8.1 cm dp.	intact
225[a]	"	"	450	439	"	0.52	6.4 cm dp.	intact
226[a]	"	"	417	396	3	3.01	3.2 cm dp.	intact
227[a]	"	"	453	458	"	3.02	7.6 cm dp.	2 pcs.
228[a]	"	"	463	404	"	2.98	6.4 cm dp.	2 pcs.
229[a]	"	"	441	410	"	3.01	4.1 cm dp.	intact
230[a]	"	"	442	331	"	2.94	5 cm dp.	2 pcs.

Note: All tests were conducted using a CAVIJET nozzle with a 0.218 cm orifice at a 2.22 cm standoff.

[a] These samples were tested in air.

Table 2

Results of safety tests of the Hydronautics CAVIJET

Test specimen: 105 mm projectile

Run No.	Shell No.	Nozzle Dia. (cm)	Nozzle Standoff (cm)	Press. (ksi)	Dur (sec.)	Result
1	1	0.218	2.22	2.9	3	0.95 cm hole, 4.3 cm dp.
2	1	0.218	2.22	6.0	5	0.95 cm hole, 8.6 cm dp.
3	1	0.218	2.22	10.0	1	1.27 cm hole, 11 cm dp.
4	1	0.218	2.22	10.0	180	1.9 cm hole, 21.4 cm dp. cavity
5	2	0.36*	0.30	3.0	60	Eroded thru to wall, about 1.27 cm thickness.
6	2	0.36*	0.30	3.0	30	Shell rotated 180 degrees from its position in run No. 5. Annular volume of Comp B completely removed along 8.1 cm length of cavity
7	1	0.36*	0.30	3.0	5	Eroded thru to wall, about 1.27 cm thickness.

*Nozzle spray pattern 45 degrees to its longitudinal axis.

Table 2

Results of safety tests of the Hydronautics CAVIJET

Test specimen: 105 mm projectile

Run No.	Shell No.	Nozzle Dia. (cm)	Nozzle Standoff (cm)	Press. (ksi)	Dur (sec.)	Result
8	1	0.36*	0.30	3.0	3	Shell rotated 180 degrees. Eroded thru to metal wall.
9	2	0.36*	0.30**	3.0	120	Eroded along side thru to metal wall.
10	2	0.36*	0.30	3.0	180	Eroded thru to wall. Temp. of water dropped from 25°C to 18°C
11	1	0.36*	0.30	10.0	75	Shell cleaned out to within 5 cm of metal bottom. Water temp. dropped 7°C during test.

*Nozzle spray pattern 45 degrees to its longitudinal axis.
**Blank end of nozzle was up against flat top of Comp B in this test.

APPENDIX B

TEST PLAN AND DATA
FOR
TASK II: OPTIMIZATION OF SYSTEM AND OPERATING PARAMETERS

TEST PLAN - TASK II

Contract DAAK10-77-C-0075

1. Part One: Calibration of Sand and Inert Filler Specimens

Configurations: a) 4 in. cubes
b) 1 in. x 4 in. x 4 in. specimens, tested in 1-in. and 4-in. directions

Test Modes: a) Stationary
b) Translating (straight-line)

Specimen-Sand Contents: 0%, 40%, 50%, 60%

Test Parameters: d, p, X, t, v, specimen orientation

Measured Parameters: h, w, V

1.1 Configuration (0% sand)

With: d, X fixed

Variables: p, t, v

Matrix: 4 in. cubes: 46 tests
1 in. x 4 in. x 4 in.: 8 tests

1.2 Sand Content Effect (stationary tests)

With: X fixed for each d; lin. orientation;
1 in. x 4 in. x 4 in.

Variables: d, p, t

Matrix: 4 sand contents, 2 d's, 3 p's: 26 tests

1.3 Orientation and Pressure Effects (stationary tests)

With: d-fixed, 60% sand, lin. x 4 in. x 4 in.

Variables: p, t, orientation

Matrix: 3 p's, 2-orientations: 48 tests

2. Part Two: Volume Removal Effectiveness Study (Rotating)

Configuration: Circular cylinders of inert filler, with 60% sand; confined in cylindrical, rotating specimen holder. Translation of single nozzle, parallel to axis of specimen cylinder.

Test Parameters: d, p, F, N, Y, θ, nozzle configuration

Measured Parameters: W, h, V

2.1 Preliminary Rotating Tests (single nozzle)

With: F and Y fixed

Variables: d, p, N, θ, nozzle configuration

Matrix: 2 d's, 3 p's, 3 N's, 2 θ's, 3 nozzle configurations: 30 tests

2.2 Pilot Hole Tests (single nozzle; preliminary)

With: F, Y, d, nozzle configuration fixed

Variables: p, N, θ

Matrix: 3 p's, 3 N's, 2 θ's: 30 tests

2.3 Cutting Head Tests (single nozzle; preliminary design)

With: Y, d, θ, nozzle configuration fixed

Variables: p, N, F, specimen diameter

Matrix: 3 p's, 3 N's, 3 F's, 2 specimen diams.: 50 tests

3. Nomenclature

d: diameter of CAVIJET™ nozzle orifice

F: feed rate (motion of cutter, parallel to specimen centerline)

L: centerline spacing between two nozzles

N: rate of rotation, rpm

p: nozzle pressure

t: duration of exposure (stationary drilling tests)

v: translation velocity

V: volume removed

w: width of slot cut by CAVIJET™

X: standoff distance

Y: offset of jet from centerline of test specimen

h: depth of slot cut by CAVIJET™

θ: angle between centerlines of specimen and nozzle

Table B-1a. Preliminary translating tests with as-received inert filler

CAVIJET® NOZZLE SIZE: 3.2 mm (0.125 in.); plain
SPECIMEN: Plain inert filler; cubes: 1 cm^3 (4 $in.^3$)
TEST MODE: Translating, submerged
STANDOFF: 3.8 cm (1.5 in.)

Run No.	Translation Velocity, v		Width of Slot, w		Depth of Slot, h		Remarks
	cm/s	in./s	mm	in.	mm	in.	
10.3 MPa (1500 psi)							
3BIa	1.37	0.54	25.4 - 31.8	1.00 - 1.25	3.18 - 6.35	0.12 - 0.25	Fairly uniform chipping.
3BIb	1.37	0.54	31.8 - 38.1	1.25 - 1.50	6.35	0.25	Slightly deeper than above.
13.8 MPa (2000 psi)							
1AIa*	30.2	11.9	--	--	--	--	Chipping action.
1AIb*	7.62	3.00	57.2	2.25	9.53	0.38	Sample cracked.
2AIa	30.2	11.9	12.7	0.50	9.53	0.38	No slotting
2BIa	14.7	5.80	9.53	0.38	1.59	0.06	No slotting - very small hole.
2BIb	14.7	5.80	6.35	0.25	0.79	0.03	No slotting.
2CIa	7.62	3.00	31.8	1.25	15.9	0.62	Chipping action - good slot.
3AIa	30.7	12.1	15.9 - 25.4	0.62 - 1.00	6.35	0.25	Chipping.
3AIb	30.5	12.0	15.9 - 25.4	0.62 - 1.00	6.35	0.25	No additional change.
3AIc	30.5	12.0	25.4 - 44.5	1.00 - 1.75	6.35	0.25	Width - 3.8 - 5.1 cm (1.5 - 2 in.).
3AId	30.5	12.0	19.1	0.75	6.35	0.25	Slight front edge addition.
3AIe	30.5	12.0	31.8 - 63.5	1.25 - 2.50	9.53	0.38	No additional change.
3AIf	30.2	11.9	31.8 - 63.5	1.25 - 2.50	9.53	0.38	No additional change.
3AIg	30.2	11.9	31.8 - 63.5	1.25 - 2.50	9.53	0.38	No additional change.
3AIh	30.2	11.9	31.8 - 63.5	1.25 - 2.50	9.53	0.38	No additional change.
3AIi	30.2	11.9	31.8 - 63.5	1.25 - 2.50	9.53	0.38	No additional change.
3AIj	30.2	11.9	31.8 - 63.5	1.25 - 2.50	9.53	0.38	Light surface damage.
15.2 MPa (2200 psi)							
4AIa	1.22	0.48	76.2	3.00	28.6 - 38.1	1.13 - 1.50	
5AIa	1.22	0.48	76.2	3.00	57.2	2.25	Sample moved.
6AIa	2.54	1.00	31.8 - 38.1	1.25 - 1.50	4.76	0.19	Sample moved after pass.
6BIa	2.79	1.10	3.53 - 15.9	0.38 - 0.62	12.7	0.50	Front edge breakout.
7AIa	15.0	5.90	--	--	--	--	No damage.
7AIb	10.2	4.00	--	--	--	--	No damage.
7AIc	7.62	3.00	--	--	--	--	Light front damage.
7BIa	7.62	3.00	--	--	--	--	No damage.
7BIb	7.62	3.00	--	--	--	--	No damage - moved.
7BIc	5.08	2.00	--	--	--	--	No damage.
7BId	5.08	2.00	--	--	--	--	Light rear breakout.
7CIa	7.62	3.00	--	--	--	--	Light rear spall.
7CIb	5.08	2.00	--	--	--	--	Rear edge breakout.
8AIa	3.81	1.50	--	--	--	--	Small rear damage only.
8AIb	2.54	1.00	--	--	--	--	Front and rear breakout.
9AIa	1.27	0.50	3.18	0.12	0.79	0.03	Perfect erosion path.
9AIIa	1.27	0.50	3.18	0.12	0.79	0.03	Perfect erosion path.
9AIIIa	1.27	0.50	3.18	0.12	0.79	0.03	Sample moved.
10AIa	1.35	0.53	--	--	--	--	Moved - path 3.8 cm (1.5 in.) from edge.
10BIa	1.27	0.50	2.38	0.09	0.79	0.03	Small groove - 75% length.

* In air, with centerbody.

Table B-1b. Preliminary stationary tests with as-received inert filler

CAVIJET® NOZZLE SIZE: 3.2 mm (0.125 in.); plain

SPECIMEN: Plain inert filler

TEST MODE: Stationary, submerged

STANDOFF: 3.8 cm (1.5 in.)

NOZZLE PRESSURE: 13.8 MPa (2000 psi)

Run No.	Cumulative Time, s	Hole Diameter, d (mm)	Hole Diameter, d (in.)	Depth of hole, h (mm)	Depth of hole, h (in.)	Remarks
Sample size: 10 cm³ (4 in.³); 10 cm (4 in.) thickness						
9BIa	1.0	6.35 - 7.94	0.25 - 0.31	0.79	0.03	Uniform hole
9BIb	2.0	38.1 - 63.5	1.50 - 2.50	7.94	0.31	Spalling effect
9BIc	3.0	38.1 - 63.5	1.50 - 2.50	7.94	0.31	Spalling effect
9BId	4.0	38.1 - 63.5	1.50 - 2.50	7.94	0.31	Spalling effect
9BIc	6.0	38.1 - 63.5	1.50 - 2.50	7.94	0.31	Spalling effect
9BIf	8.0	38.1 - 63.5	1.50 - 2.50	7.94	0.31	Hole increased and cracked
11AIa	1.0	6.35	0.250	0.79	0.03	Uniform hole
11AIb	2.0	31.8 - 63.5	1.25 - 2.50	28.6	1.13	Cracked
Top orientation; Sample size: 10 x 10 x 2.5 cm (4 x 4 x 1 in.); 2.5 cm (1 in.) thickness						
12AIa	3.0	6.35	0.25	25.4	1.00	Sample cracked
13AIa	2.0	12.7	0.50	25.4	1.00	Cracked
14AIa	1.0	12.7 - 31.8	0.50 - 1.25	6.35 - 7.94	0.25 - 0.31	Cracked
15AIa	1.0	4.76 - 6.35	0.19 - 0.25	12.7	0.50	Cracked
Edge orientation; Sample size: 10 x 10 x 2.5 cm (4 x 4 x 1 in.); 10 cm (4 in.) thickness						
16AIa	1.0	9.53	0.38	1.59	0.06	Light spall
16AIb	2.0	25.4	1.00	7.94 - 12.7	0.31 - 0.50	Some breakout and erosion
16BIa	2.0	19.1 - 25.4	0.75 - 1.00	6.35 - 12.7	0.25 - 0.50	-----
16BIb	4.0	25.4	1.00	9.53 - 15.9	0.38 - 0.62	Spalling to one side

Table B-2. Effect of sand content on erosion of inert filler mixture for explosive simulation

CAVIJET® NOZZLE SIZE: 3.2 mm (0.125 in.); plain

SPECIMEN: Sand and inert filler; squares: 10 x 10 x 2.5 cm (4 x 4 x 1 in.)

TEST MODE: Stationary, submerged

STANDOFF: 3.8 cm (1.5 in.)

Run No.	Cumulative Time, s	Removed Volume		Volume Removal Rate, $\dot{V}$		Volume Removal Effectiveness, e_v		Percent Sand by Weight
		$10^{-6} m^3$	$10^{-5} ft^3$	$10^{-3} m^3/hr$	$10^{-1} ft^3/hr$	$10^{-4} m^3/kw\text{-}hr$	$10^{-2} ft^3/hp\text{-}hr$	
10.3 MPa (1500 psi)								
22AIa	1.0	3.51	12.1	13.0	4.46	18.8	4.95	40%
23AIa	1.0	0.95	3.37	3.32	1.21	4.97	1.31	60%
23AIb	2.0	1.20	4.24	2.15	0.763	3.02	0.795	60%
23AIc	3.0	1.30	4.59	1.56	0.551	2.16	0.570	60%
23AId	4.0	5.49	19.4	4.95	1.75	6.91	1.82	60%
23AIe	5.0	6.23	22.0	4.47	1.58	6.27	1.65	60%
23AIf	6.0	6.91	24.4	4.13	1.46	5.77	1.52	60%
23AIg*	7.0	--	--	--	--	--	--	60%
24AIa	1.0	0.793	2.80	2.86	1.01	3.99	1.05	60%
24AIb	2.0	2.89	10.2	5.21	1.84	7.25	1.91	60%
24AIc	3.0	3.20	11.3	3.79	1.34	5.28	1.39	60%
24AId	4.0	10.2	36.0	9.17	3.24	12.8	3.38	60%
24AIe	5.0	10.5	37.1	7.56	2.67	10.6	2.78	60%
24AIf**	6.0	--	--	--	--	--	--	60%
13.8 MPa (2000 psi)								
17AIa	1.0	0.100	0.353	0.359	0.127	0.668	0.176	60%
17AIb	2.0	0.799	2.82	1.44	0.507	2.37	0.704	60%
17AIc	3.0	0.901	3.18	1.08	0.382	2.02	0.531	60%
17AId	4.0	1.00	3.53	0.900	0.318	1.68	0.442	60%
17AIe	5.0	1.05	3.71	0.756	0.267	1.41	0.371	60%
17AIf	7.0	1.30	4.59	0.671	0.237	1.25	0.329	60%
17AIg	9.0	9.01	31.8	3.60	1.27	6.68	1.76	60%
18AIa	5.0	9.99	28.3	5.78	2.04	10.8	2.83	60%
19AIa	5.0	1.50	4.24	0.864	0.305	1.61	0.423	0%
20AIa	1.0	0.170	0.602	0.615	0.217	0.566	0.149	50%
21AIa	1.0	3.54	12.5	12.7	4.50	11.7	3.09	40%
69.0 MPa (10,000 psi)								
1[illegible]b*	1.0	--	--	--	--	--	--	0%

*Eroded through specimen, no volume measurement.

**Specimen cracked and jet eroded through, no volume measurements.

Table B-3. Tests with inert filler/60 percent sand mixture: to derive scale factor

CAVIJET® NOZZLE SIZE: 2.2 mm (0.086 in.), plain

SPECIMEN: Inert filler/60 percent sand mixture; squares: 10 x 10 x 2.5 cm (4 x 4 x 1 in.)

TEST MODE: Stationary, submerged

STANDOFF: 2.2 cm (0.875 in.)

Nozzle Pressure		Run No.	Cumulative Time,	Removed Volume		Volume Removal Rate, $\dot{V}$		Volume Removal Effectiveness, e_v	
MPa	psi		s	$10^{-6}m^3$	$10^{-3}ft^3$	$10^{-2}m^3/hr$	ft^3/hr	$10^{-4}m^3/kw\text{-}hr$	$10^{-3}ft^3/hp\text{-}hr$
Top orientation (2.5 cm (1 in.) thickness)									
20.7	3,000	30AIa	0.53	1.96	0.069	1.26	0.445	11.9	3.14
		30AIb	1.00	2.16	0.077	0.779	0.275	7.37	1.94
		30AIc	1.52	2.63	0.093	0.623	0.220	5.89	1.55
		31AIa	0.54	0.566	0.020	0.377	0.133	3.58	0.943
		31AIb	1.02	0.878	0.031	0.309	0.109	2.93	0.772
		31AIc	1.59	1.70	0.060	0.385	0.136	3.65	0.961
		32AIa	1.05	1.60	0.056	0.547	0.193	5.20	1.37
		52AIa	0.57	7.84	0.277	4.95	1.75	46.8	12.3
		53AIa	0.47	11.8	0.417	9.04	3.19	85.6	22.5
		54AIa	0.35	9.48	0.335	9.76	3.45	92.3	4.3
		54AIb	0.58	20.7	0.730	12.8	4.53	121.0	32.0
		56AIa	0.32	0.825	0.029	0.928	0.328	8.77	2.31
		56AIb	0.62	1.80	0.064	1.05	0.370	9.91	2.61
		56AIc	1.00	2.16	0.077	0.779	0.275	7.37	1.94
		57AIa	0.28	0.258	0.009	0.331	0.117	3.14	0.826
		57AIb	0.53	0.412	0.015	0.280	0.099	2.65	0.698
		57AIc	0.89	0.773	0.027	0.313	0.110	2.96	0.779
		58AIa	0.63	1.80	0.064	1.03	0.364	9.76	2.57
		59AIa	0.57	1.49	0.053	0.944	0.333	8.92	2.35
30.9	4,500	33AIa	0.22	0.368	0.013	0.589	0.208	3.02	0.795
		33AIb	0.54	1.55	0.055	1.45	0.512	7.41	1.95
		34AIa	0.23	2.07	0.073	0.323	0.114	1.65	0.435
		34AIb	0.54	1.60	0.056	1.62	0.571	8.24	2.17
		35AIa	0.44	1.49	0.053	1.22	0.432	6.27	1.65
		60AIa	0.30	1.80	0.064	2.16	0.765	11.1	2.91
		61AIa	0.33	3.09	0.109	3.37	1.190	17.2	4.54
		62AIa	0.38	0.623	0.022	0.586	0.207	2.99	0.787
		63AIa	0.33	20.00	0.706	21.8	7.71	111.0	29.4
		55AIa	0.25	0.319	0.011	0.445	0.157	2.27	0.598
		55AIb	0.48	0.319	0.011	0.481	0.170	2.47	0.651
41.2	6,000	36AIa	0.33	4.28	0.151	4.67	1.65	15.4	4.06
		37AIa	0.23	7.22	0.255	1.13	0.399	3.73	0.983
		38AIa	0.21	5.67	0.200	0.971	0.343	3.21	0.846
		64AIa	0.35	2.42	0.086	2.49	0.880	8.24	2.17
Edge Orientation (10 cm (4 in.) thickness)									
20.7	3,000	39AIa	1.06	4.33	0.153	1.47	0.519	13.9	3.66
		40AIa	1.05	14.4	0.508	4.93	1.74	46.7	12.3
		41AIa	1.02	2.06	0.073	0.728	0.257	6.87	1.81
		42AIa	0.51	1.49	0.053	1.06	0.373	9.99	2.63
		43AIa	0.59	6.70	0.237	4.09	1.44	3.87	1.02
		51AIa	0.52	9.59	0.339	6.64	2.34	62.8	16.5
30.9	4,500	44AIa	1.09	4.07	0.144	1.34	0.475	6.87	1.81
		45AIa	1.09	2.94	0.104	0.971	0.343	4.97	1.31
		46AIa[a]	1.00	-	-	-	-	-	-
41.[illegible]	6,000	47AIa	0.48	11.3	0.399	8.47	0.299	28.0	7.36
		48AIa[a]	0.30	-	-	-	-	-	-
		49AIa	0.26	1.03	0.036	1.43	0.504	4.71	1.24
		50AIa	0.44	13.2	0.466	10.8	3.81	35.7	9.39

[a] Specimen split - pieces missing

Table B-4. Tests with Composition B: to derive scale factor

CAVIJET® NOZZLE SIZE: 2.2 cm (0.086 in.); plain

SPECIMEN: Composition B; square: 10 x 10 x 2.5 cm (4 x 4 x 1 in.)

TEST MODE: Stationary, submerged (except as noted)

STANDOFF: 2.2 cm (0.875 in.)

Nozzle Pressure		Run No.	Exposure Time,	Removed Volume		Volume Removal Rate, $\dot{V}$		Volume Removal Effectiveness, e_v	
MPa	psi		s	$10^{-5}m^3$	$10^{-3}ft^3$	$10^{-1}m^3/hr$	ft^3/hr	$10^{-3}m^3/kw\text{-}hr$	$10^{-1}ft^3/hp\text{-}hr$
Top orientation (2.5 cm (1 in.) thickness)									
13.8	2,000	31	5.98	0.706	0.249	0.042	0.148	0.741	0.195
		32	5.03	0.059	0.021	0.004	0.015	0.346	0.019
		33	6.99	0.118	0.042	0.061	0.021	0.106	0.028
17.3	2,500	34	4.91	0.235	0.083	0.017	0.061	0.213	0.056
		35	5.12	0.118	0.042	0.008	0.029	0.103	0.027
		36	4.94	0.235	0.083	0.017	0.061	0.213	0.056
		37	5.07	0.176	0.062	0.013	0.044	0.156	0.041
20.7	3,000	38	5.05	1.24	0.436	0.088	0.311	0.832	0.219
		39	3.08	2.59	0.914	0.303	1.07	2.86	0.754
		40	0.91	0.235	0.083	0.093	0.329	0.881	0.232
41.4	6,000	41	0.26	1.47	0.519	2.04	7.19	6.72	1.77
		43	0.29	2.12	0.748	2.63	9.28	8.70	2.29
		44	0.33	1.65	0.582	1.80	6.35	5.92	1.56
		45	0.31	0.941	0.332	1.09	3.86	3.61	0.951
		46	0.31	1.18	0.415	1.37	4.82	4.52	1.19
		48	0.33	1.00	0.353	1.09	3.85	3.60	0.949
		49	0.30	0.647	0.229	0.776	2.74	2.56	0.675
		50	0.30	0.647	0.229	0.776	2.74	2.56	0.675
69.0	10,000	51[b]	0.26	7.47	2.64	0.103	36.5	15.7	4.12
		52[a]	0.31	1.94	0.686	2.25	7.96	3.41	0.898
		53[b]	0.26	3.24	1.14	4.48	15.8	6.76	1.78
		54[a]	0.31	0.588	0.208	0.683	2.41	1.03	0.272
		55	0.32	3.00	1.06	3.38	11.9	5.09	1.34
		56	0.31	4.82	1.70	5.60	19.8	8.47	2.23
		57[b]	0.30	10.8	3.80	12.9	45.6	19.6	5.15
		58	0.30	2.00	0.706	2.40	8.48	3.63	0.956
		59	0.21	2.71	0.956	4.64	16.4	7.03	1.85
		60[a]	0.23	1.82	0.643	2.85	10.1	4.33	1.14
Edge Orientation (10 cm (4 in.) thickness)									
20.7	3,000	62	5.00	3.65	1.29	0.263	0.927	2.48	0.654
		64	20.06	5.18	1.83	0.093	0.328	0.881	0.232
		65	20.0	3.71	1.31	0.067	0.236	0.631	0.166
		66	19.9	4.53	1.60	0.082	0.289	0.777	0.204
		67	20.07	2.65	0.953	0.047	0.168	0.448	0.118
		68	20.05	6.59	2.33	0.118	0.418	1.12	0.295
		151[b]	2.98	3.35	1.18	0.405	1.43	3.84	1.01
		152[b]	3.05	2.88	1.02	0.340	1.20	3.22	0.848
		153[b]	3.01	5.53	1.95	0.661	2.34	6.27	1.65
		154[b]	3.00	3.65	1.29	0.438	1.55	4.14	1.09
		155[b]	2.96	3.41	1.20	0.415	1.47	3.91	1.03
		156	5.05	1.88	0.665	0.134	0.474	1.27	0.334
		157	5.02	0.882	0.312	0.063	0.223	0.600	0.158
		158[b]	5.01	4.12	1.45	0.296	1.04	2.80	0.737
		159	5.03	0.706	0.249	0.051	0.178	0.479	0.126
		160	4.96	2.24	0.789	0.162	0.573	1.53	0.404
		161[b]	10.05	6.18	2.18	0.221	0.781	2.09	0.551
		162	10.06	3.06	1.08	0.109	0.387	1.04	0.273
		163[b]	10.04	4.59	1.62	0.165	0.581	1.56	0.410
		164	10.00	4.88	1.72	0.176	0.621	1.66	0.438

[a]Erosion plus fracture

[b]Maximum fracturing — missing pieces

Table B-4. (Concluded)

Nozzle Pressure		Run No.	Exposure Time,	Removed Volume		Volume Removal Rate, $\dot{V}$		Volume Removal Effectiveness, e_v	
MPa	psi		s	$10^{-5}m^3$	$10^{-3}ft^3$	$10^{-1}m^3/hr$	ft^3/hr	$10^{-3}m^3/kw\text{-}hr$	$10^{-1}ft^3/hp\text{-}hr$
20.7	3,000	165	10.00	2.06	0.727	0.074	0.262	0.703	0.185
		166	20.02	3.35	1.18	0.060	0.213	0.570	0.150
		167	19.98	4.65	1.29	0.066	0.232	0.619	0.163
		168[b]	20.04	6.88	2.43	0.124	0.437	1.17	0.308
		169	19.98	8.24	2.91	0.148	0.524	1.41	0.370
		170	19.99	2.35	0.831	0.042	0.150	0.403	0.106
		171	31.04	5.71	2.02	0.066	0.234	0.627	0.165
		174	30.03	9.41	3.32	0.112	0.398	1.07	0.281
		176[b]	15.00	22.2	7.83	0.532	1.88	5.05	1.33
		177	15.04	4.06	1.43	0.097	0.343	0.919	0.242
		178[b]	15.04	10.9	3.84	0.260	0.920	2.46	0.649
		179	15.03	6.29	2.22	0.151	0.532	1.43	0.376
		180	15.04	5.47	1.93	0.131	0.462	1.24	0.326
		226[c]	3.01	1.24	0.395	0.148	0.522	1.48	0.390
		227[b,c]	3.02	2.88	1.93	0.344	1.21	1.40	0.368
		228[b,c]	2.98	3.47	1.23	0.042	1.48	3.95	1.04
		229[c]	3.01	1.82	0.644	0.022	0.77	2.07	0.544
		230[b,c]	2.94	6.53	2.31	0.080	2.82	7.56	1.99
41.4	6,000	71	0.26	1.00	0.353	1.38	4.89	4.56	1.20
		72[b]	1.02	7.29	2.58	2.57	9.09	8.51	2.24
		73	1.12	1.71	0.602	0.548	1.94	1.81	0.477
		76	3.13	3.59	1.27	0.413	1.46	1.36	0.359
		79	4.00	2.53	0.893	0.228	0.804	0.752	0.198
69.0	10,000	81[a]	0.26	0.471	0.166	0.652	2.30	0.987	0.260
		82[a]	0.54	1.29	0.457	0.863	3.05	1.31	0.344
		83[b]	0.50	4.29	1.52	3.09	10.9	4.67	1.23
		84[b]	0.55	3.41	1.20	2.23	7.89	3.38	0.890
		85[b]	0.48	3.24	1.14	2.43	8.57	3.67	0.967
		86	0.35	4.88	1.72	5.02	17.7	7.60	2.00
		87	0.52	9.06	3.20	6.27	22.2	9.49	2.50
		88[a]	0.58	3.24	1.15	2.01	7.09	3.04	0.800
		89[a]	0.53	3.00	1.06	2.04	7.20	3.08	0.812
		90[b]	0.53	4.65	1.64	3.16	11.2	4.79	1.26
		181[a]	0.28	1.12	0.395	1.44	1.43	2.17	0.572
		182[b]	0.25	5.47	1.93	7.88	1.20	11.9	3.14
		183[b]	0.35	4.94	1.74	5.08	2.34	7.67	2.02
		184[a]	0.22	3.12	1.10	5.10	1.55	7.71	2.03
		185[a]	0.28	6.18	2.18	7.94	28.0	12.0	3.16
		186[a]	0.27	1.00	0.353	1.33	4.71	2.02	0.531
		187[a]	0.28	1.76	0.623	2.27	8.01	3.43	0.904
		188[a]	0.34	3.47	1.23	3.67	13.0	5.54	1.46
		189[b]	0.24	1.00	0.353	1.50	5.30	2.27	0.597
		190	0.25	27.1	9.58	39.0	138.	59.2	15.6
		216[c]	0.38	13.4	4.72	12.7	44.7	19.1	5.04
		217[c]	0.23	6.29	2.22	9.85	34.8	14.9	3.92
		218[c]	0.29	3.65	1.29	4.53	16.0	6.84	1.80
		219[c]	0.27	1.06	0.374	1.41	4.99	2.13	0.562
		220[c]	0.22	1.29	0.457	2.12	7.48	3.20	0.843

[a]Erosion plus fracture

[b]Maximum fracturing — missing pieces

[c]Tested in air

Table B-5a. Preliminary rotating tests

CAVIJET® NOZZLE SIZE: 3.2 mm (0.125 in.); plain

SPECIMEN: Inert filler/60 percent sand mixture; cylinders: 10 cm diameter x 10 cm length (4 in. dia. x 4 in. length)

TEST MODE: Rotating, submerged

NOZZLE TRANSLATION RATE: 8.4 mm/s (0.33 in./s)

Nozzle Pressure		Run No.	Rotation,	Specimen Exposure Time,	Removed Volume		Volume Removal Rate, $\dot{V}$		Volume Removal Effectiveness, e_v	
MPa	psi		rpm	s	10^{-4} m^3	10^{-3} ft^3	10^{-2} m^3/hr	ft^3/hr	10^{-3} m^3/kw-hr	10^{-2} ft^3/hp-hr
45° impingement angle; Standoff: 1.3 to 5.1 cm (0.50 to 2 in.)										
20.7	3,000	27AIa*	80	3.0						
		27AIb*	40	6.0						
27.6	4,000	27AIc*	40	8.63						
		27BIa*	40	3.0						
33.8	4,900	28AIa*	40	2.78						
35.2	5,100	28BIa*	40	3.13						
30° impingement angle; Standoff: 0.95 to 7.6 cm (0.38 to 3 in.)										
20.7	3,000	78AIa	20	6.99	1.14	4.04	5.89	2.08	2.91	7.67
		79AIa	20	7.20	0.957	3.38	4.79	1.69	2.37	6.23
		84AIa	20	7.20	1.21	4.29	6.09	2.15	3.00	7.91
		85AIa	20	7.20	0.830	2.93	4.16	1.47	2.05	5.40
27.6	4,000	80AIa	20	7.20	0.980	3.46	4.90	1.73	1.60	4.16
		81AIa	20	7.20	1.11	3.93	5.58	1.97	1.80	4.73
34.5	5,000	82AIa	20	7.20	1.46	5.14	7.28	2.57	1.70	4.47
		83AIa	20	7.20	1.11	3.93	5.58	1.97	1.30	3.42

*Preliminary tests to establish testing technique - weight loss not recorded.

Table B-5b. Effects of pressure and rpm: preliminary rotating tests

CAVIJET® NOZZLE SIZE: 3.6 mm (0.14 in.); plain

SPECIMEN: Inert filler/60 percent sand mixture; cylinder: 10 cm diameter x 10 cm length (4 in. dia. x 4 in. length)

TEST MODE: Rotating, submerged

STANDOFF: Noted in table

IMPINGEMENT ANGLE: 30°

NOZZLE TRANSLATION RATE: 8.4 mm/s (0.33 in./s)

Nozzle Pressure		Run No.	Rotation,	Specimen Exposure Time,	Removed Volume		Volume Removal Rate, $\dot{V}$		Volume Removal Effectiveness, e_v	
MPa	psi		rpm	s	$10^{-4} m^3$	$10^{-3} ft^3$	$10^{-2} m^3/hr$	ft^3/hr	$10^{-3} m^3/kw\text{-}hr$	$10^{-2} ft^3/hp\text{-}hr$
Straight flow path into nozzle; Standoff: 0.95 to 7.6 cm (0.38 to 3.0 in.)										
20.7	3,000	76AIa	20	7.03	0.934	3.30	4.79	1.69	1.82	4.78
		77AIa	20	6.82	1.22	4.30	6.43	2.27	2.44	6.43
		86AIc	20	6.64	1.34	4.72	7.25	2.56	2.75	7.23
		87AIa	20	6.44	0.818	2.89	4.59	1.62	1.79	4.58
		88AIa	20	6.25	1.40	4.93	8.04	2.84	3.05	8.04
27.6	4,000	74AIa	20	7.58	1.73	6.10	8.21	2.90	2.01	5.28
		75AIa	20	7.58	1.55	5.49	7.39	2.61	1.80	4.75
34.5	5,000	72AIa	20	7.58	2.59	9.15	12.3	4.35	2.16	5.69
		73AIa	20	7.35	3.80	13.4	18.6	6.58	3.27	8.61
Flow into nozzle angled at 45°; Standoff: 4.8 to 9.5 cm (1.9 to 3.8 in.)										
20.7	3,000	65AIa	40	6.06	0.068	0.240	0.402	0.142	0.153	0.403
27.6	4,000	66AIa	40	6.25	0.084	0.296	0.481	0.170	0.118	0.311
		67AIa	40	6.06	0.084	0.296	0.498	0.176	0.122	0.321
34.5	5,000	68AIa	40	5.71	0.237	0.837	1.50	0.528	0.262	0.690
		69AIa	40	6.06	0.283	0.998	1.68	0.593	0.295	0.776
		70AIa	20	6.06	2.23	7.87	13.3	4.68	2.32	6.12
		71AIa	20	5.88	0.329	1.16	2.01	0.711	0.354	0.931

Table B-6. Tests with preliminary pilot hole CAVIJET® nozzle orientations

CAVIJET® NOZZLE SIZE: 3.2 mm (0.125 in.); plain

SPECIMEN: Inert filler/60 percent sand mixture; cylinders: 10 cm diameter x 10 cm length (4 in. dia. x 4 in. length)

TEST MODE: Rotating, submerged

STANDOFF: Noted in table

NOZZLE TRANSLATION RATE: 8.4 mm/s (0.33 in./s)

Nozzle Pressure		Run No.	Rotation,	Δx*		Specimen Exposure Time,	Removed Volume		Volume Removal Rate, $\dot{V}$		Volume Removal Effectiveness, e_v	
MPa	psi		rpm	cm	in.	s	10^{-4} m^3	10^{-3} ft^3	10^{-2} m^3/hr	ft^3/hr	10^{-3} m^3/kw-hr	10^{-2} ft^3/hp-hr
30° impingement angle; Standoff: 0.64 to 10 cm (0.25 to 4 in.)												
27.6	4,000	106AIa	80	0	0	10.61	2.61	9.22	8.86	3.13	2.86	7.53
		107AIa	80	5.08	2.00	15.15	3.68	13.0	8.75	3.09	2.83	7.44
		110AIa	40	0	0	10.61	2.08	7.34	7.05	2.49	2.28	6.00
		111AIa	40	5.08	2.00	15.94	5.86	20.7	13.3	4.67	4.22	11.2
		112AIa	40	3.81	1.50	14.49	4.56	16.1	11.4	4.01	3.66	9.65
34.5	5,000	104AIa	80	0	0	10.67	2.38	8.41	8.04	2.84	1.88	4.94
		105AIa	80	5.08	2.00	15.95	5.95	21.0	13.5	4.75	3.14	8.27
		108AIa	80	5.08	2.00	16.77	6.29	22.2	13.5	4.77	3.15	8.30
		109AIa	40	5.08	2.00	15.94	5.41	19.1	12.2	4.30	2.84	7.49
		103AIa	40	5.08	2.00	16.67	5.92	20.9	12.8	4.51	2.98	7.84
45° impingement angle; Standoff: 0.64 to 7.6 cm (0.25 to 3 in.)												
20.7	3,000	100AIa	40	0	0	6.19	0.547	1.93	3.20	1.13	1.58	4.15
		101AIa	40	0	0	6.06	0.952	3.36	5.66	2.00	2.80	7.37
27.6	4,000	90BIa	20	0	0	6.19	1.05	3.72	6.12	2.16	1.98	5.21
		91AIa	20	0	0	6.10	0.974	3.44	5.75	2.03	1.86	4.89
		98AIa	40	0	0	6.10	0.555	1.96	3.29	1.16	1.06	2.79
		99AIa	40	1.27	0.50	7.62	1.35	4.76	6.37	2.25	2.06	5.42
34.5	5,000	92AIa	20	2.54	1.00	9.09	2.27	8.00	8.98	3.17	2.09	5.51
		93AIa	40	2.54	1.00	8.40	3.99	14.1	17.1	6.03	3.99	10.5
		94AIa	40	5.08	2.00	10.99	4.22	14.9	13.9	4.89	3.23	8.50
		95AIa	40	5.08	2.00	12.62	5.38	19.0	15.4	5.43	3.59	9.45
		96AIa	80	0	0	6.31	0.776	2.74	4.42	1.56	1.03	2.72
		97AIa	80	2.54	1.00	9.15	2.23	7.89	8.90	3.10	2.05	5.40
		102AIa	40	5.08	2.00	11.59	4.84	17.1	15.0	5.30	3.50	9.22

*Distance traveled by nozzle: past the original surface of the specimen.

Table B-7a. Cutting head tests: precast fuze hole specimens, using total weight loss

CAVIJET® NOZZLE SIZE: 3.2 mm (0.125 in.); plain

SPECIMEN: Inert filler/60 percent sand mixture; cylinders: 10 cm. diameter x 10 cm
Length (4 in. diameter x 4 in. length), with fuze hole 7.6 cm deep x 5.0 cm diameter
(3 in. deep x 2 in. diameter)

TEST MODE: Rotating, submerged, with cover plate

STANDOFF: Noted in table

NOZZLE TRANSLATION RATE: 8.4 mm/s (0.33 in./s)

Nozzle Pressure		Run No.	Rotation,	Specimen Exposure Time,	Change in Radius Size				Volume Removal Rate, $\dot{V}$		Volume Removal Effectiveness, e_v	
					Top		Bottom					
MPa	psi		rpm	s	mm	in.	mm	in.	$10^{-2} m^3/hr$	ft^3/hr	$10^{-3} m^3/kw\text{-}hr$	$10^{-2} ft^3/hp\text{-}hr$
30° impingement angle; Standoff: 0.64 to 5.3 cm (0.25 to 2.1 in.)												
27.6	4,000	141AIa	40	15.0	0	0	0.28	0.011	3.71	1.31	1.20	3.15
		142AIa	40	15.0	0	0	0.15	0.006	3.43	1.21	1.10	2.91
		143AIa	80	15.2	0	0	0.46	0.018	3.34	1.18	1.08	2.84
		144AIa	80	15.2	0.08	0.003	0.33	0.013	3.48	1.23	1.12	2.96
		145AIa	120	14.8	0	0	0.02	0.001	3.65	1.29	1.18	3.11
		146AIa	120	16.1	0	0	0	0	3.23	1.14	1.04	2.75
		147AIa	158	14.9	0.20	0.008	0.41	0.016	3.37	1.19	1.09	2.87
		148AIa	158	15.2	0.76	0.030	0.28	0.011	3.37	1.19	1.09	2.87
34.5	5,000	114AIa	40	14.4	0.51	0.020	2.16	0.085	3.94	1.39	0.919	2.42
		115AIa	80	14.4	1.27	0.050	7.49	0.295	5.66	2.00	1.32	3.48
		116AIa	80	14.8	1.02	0.040	8.00	0.315	4.84	1.71	1.13	2.98
		117AIa	40	14.8	0.89	0.035	3.56	0.140	4.56	1.61	1.06	2.80
		149AIa	158	14.8	1.09	0.043	14.0	0.551	5.83	2.06	1.36	3.59
		150AIa	158	15.2	2.41	0.095	16.0	0.631	5.86	2.07	1.37	3.60
		151AIa	120	14.6	1.91	0.075	20.1	0.791	6.34	2.24	1.48	3.90
		152AIa	120	14.8	2.67	0.105	19.1	0.751	8.61	3.04	2.01	5.29
45° impingement angle; Standoff: 0.64 to 3.8 cm (0.25 to 1.5 in.)												
27.6	4,000	133AIa	158	12.7	0	0	2.29	0.090	4.56	1.61	1.47	3.88
		134AIa	158	12.1	0	0	3.18	0.125	5.75	2.03	1.86	4.89
		135AIa	120	12.5	0	0	3.81	0.150	5.47	1.93	1.77	4.65
		136AIa	120	12.7	0	0.	3.51	0.138	4.62	1.63	1.49	3.92
		137AIa	80	12.7	0	0	3.81	0.150	5.13	1.81	1.66	4.36
		138AIa	80	12.9	0	0	2.57	0.101	4.62	1.63	1.49	3.92
		139AIa	40	12.1	0	0	0.96	0.038	5.55	1.96	1.79	4.72
		140AIa	40	12.3	0	0	1.60	0.063	5.18	1.83	1.67	4.41
34.5	5,000	129AIa*	120	12.1	0.46	0.018	6.43	0.253	2.32	0.818	0.539	1.42
		130AIa*	120	12.5	0.43	0.017	5.79	0.228	1.93	0.683	0.452	1.19
		131AIa*	158	11.9	2.03	0.080	7.95	0.313	3.29	1.16	0.767	2.02
		132AIa	158	12.1	1.52	0.060	8.26	0.325	7.96	2.81	2.57	6.77
		153AIa	80	12.3	2.49	0.098	17.8	0.701	8.81	3.11	2.05	5.41
		154AIa	80	11.7	3.81	0.150	15.3	0.601	8.38	2.96	1.96	5.15
		155AIa	40	12.5	--	--	14.0	0.551	8.47	2.99	1.97	5.20
		156AIa	40	12.3	1.22	0.048	12.2	0.481	5.98	2.11	1.39	3.67
		157AIa	40	11.7	1.52	0.060	13.5	0.531	7.39	2.61	1.72	4.54

* [illegible] by [illegible]koff.

Table B-7b. Cutting head tests: precast fuze hole specimens, using partial weight loss (excluding losses from base breakoff)

CAVIJET® NOZZLE SIZE: 3.2 mm (0.125 in.); plain

SPECIMEN: Inert filler/60 percent sand mixture; cylinders: 10 cm diameter x 10 cm length (4 in. diameter x 4 in. length), with fuze hole 7.6 cm deep x 5.0 cm diameter (3 in. deep x 2 in. diameter)

TEST MODE: Rotating, submerged, with cover plate

STANDOFF: Noted in table

NOZZLE TRANSLATION RATE: 8.4 mm/s (0.33 in./s)

Nozzle Pressure		Run No.	Rotation,	Specimen Exposure Time,	Volume Removal Rate, $\dot{V}$		Volume Removal Effectiveness, e_v	
MPa	psi		rpm	s	$10^{-2}m^3/hr$	ft^3/hr	$10^{-3}m^3/kw\text{-}hr$	$10^{-2}ft^3/hp\text{-}hr$
30° impingement angle; Standoff: 0.64 to 5.3 cm (0.25 to 2.1 in.)								
27.6	4,000	141AIa	40	10.8	0.872	0.308	0.282	0.742
		142AIa	40	10.8	0.470	0.166	0.152	0.400
		143AIa	80	11.0	0.385	0.136	0.124	0.327
		144AIa	80	11.0	0.606	0.214	0.196	0.515
		145AIa	120	10.6	0.694	0.245	0.224	0.590
		146AIa	120	11.0	0.076	0.027	0.247	0.650
		147AIa	158	10.8	0.578	0.204	0.186	0.491
		148AIa	158	10.8	0.249	0.088	0.080	0.212
34.5	5,000	114AIa	40	9.85	0.125	0.044	0.029	0.076
		115AIa	80	9.85	2.63	0.928	0.615	1.62
		116AIa	80	10.6	2.39	0.845	0.558	1.47
		117AIa	40	10.6	2.01	0.709	0.467	1.23
		149AIa	158	9.85	2.69	0.949	0.627	1.65
		150AIa	158	10.4	2.75	0.972	0.642	1.69
		151AIa	120	10.6	4.76	1.68	1.11	2.92
		152AIa	120	7.85	3.20	1.13	0.748	1.97
45° impingement angle; Standoff: 0.64 to 3.8 cm (0.25 to 1.5 in.)								
27.6	4,000	133AIa	158	10.8	0.207	0.073	0.067	0.176
		134AIa	158	9.85	0.487	0.172	0.157	0.414
		135AIa	120	10.4	0.765	0.270	0.247	0.650
		136AIa	120	10.8	0.255	0.090	0.082	0.217
		137AIa	80	11.0	1.26	0.446	0.406	1.07
		138AIa	80	11.0	0.354	0.125	0.114	0.301
		139AIa	40	10.6	1.97	0.695	0.634	1.67
		140AIa	40	10.8	1.63	0.577	0.528	1.39
34.5	5,000	129AIa*	120	12.1	2.32	0.818	0.539	1.42
		130AIa*	120	12.5	1.93	0.683	0.452	1.19
		131AIa*	158	11.9	3.29	1.16	0.767	2.02
		132AIa	158	10.2	4.02	1.42	0.938	2.47
		153AIa	80	9.85	7.05	2.49	1.64	4.33
		154AIa	80	10.2	4.53	1.60	1.06	2.78
		155AIa	40	9.85	7.50	2.65	1.75	4.61
		156AIa	40	11.0	3.79	1.34	0.885	2.33
		157AIa	40	9.47	6.85	2.42	1.60	4.21

*No base breakoff

Table B-7c. Cutting head tests: with cover plate and without precast fuze holes

CAVIJET® NOZZLE SIZE: 3.2 mm (0.125 in.); plain

SPECIMEN: Inert filler/60 percent sand mixture; cylinders: 10 cm diameter x 10 cm length (4 in. diameter x 4 in. length), no fuze hole

TEST MODE: Rotating, submerged, with cover plate

STANDOFF: Noted in table

NOZZLE TRANSLATION RATE: 8.4 mm/s (0.33 in./s)

Nozzle Pressure		Run No.	Rotation,	Specimen Exposure Time,	Volume Removal Rate, $\dot{V}$		Volume Removal Effectiveness, e_v	
MPa	psi		rpm	s	10^{-2} m^3/hr	ft^3/hr	10^{-3} $m^3/kw\text{-}hr$	10^{-2} $ft^3/hp\text{-}hr$
30° impingement angle; Standoff: 0.64 to 5.3 cm (0.25 to 2.1 in.)								
27.6	4,000	123AIa	80	7.58	15.2	5.37	4.90	12.9
		124AIa	80	7.58	12.5	4.40	4.02	10.6
		125AIa	40	7.58	14.8	5.21	4.75	12.5
		126AIa	40	7.58	15.7	5.54	5.05	13.3
34.5	5,000	118AIa	40	8.33	12.1	4.28	2.83	7.45
		119AIa	40	9.09	16.8	5.94	3.91	10.3
		120AIa	40	8.33	11.8	4.15	2.74	7.22
		121AIa	80	7.58	11.9	4.20	2.78	7.31
		122AIa	80	11.4	17.6	6.22	4.10	10.8
45° impingement angle; Standoff: 0.64 to 3.8 cm (0.25 to 1.5 in.)								
34.5	5,000	127AIa	40	4.92	19.1	6.74	4.44	11.7
		128AIa	80	4.17	15.0	5.30	3.50	9.22

APPENDIX C

ENERGY AND ECONOMIC

ANALYSIS

Factors Used in Energy and Economic Comparisons

1. Projectiles to be considered:

   a. 155 mm M549 RAP

   b. 8-inch XM650 RAP

2. Production Rates - Line capability on a 3 shift: 8 hour day: 5 day week at Iowa AAP:

   a. 155 mm M549 - 798,000/year

   b. 8-inch XM650 - 108,000/year

3. Projected Reject Rate @ 5%:

   a. 155 mm M549 - 39,900/year

   b. 8-inch XM650 - 5,400/year

4. Costs:

   a. Steam - projected @ $4.50 per 454 kg (1000 lbs)

   b. Electricity - projected @ $0.055 per kWh

   c. Labor - $20.00 per man-hour (includes overhead, fringe, etc.)

   d. Water - $0.50 per 3785 l (1000 gal)

   e. Water Treatment - $4.00 per 3785 l (1000 gal)

5. Other:

   a. Energy content of steam - 2.326×10^6 joules per kg (1000 BTU per lb)

   b. Mass of Composition B in:

      1. 155 mm M549 - 7.26 kg (16 lb)

      2. 8-inch XM650 - 11.8 kg (26 lb)

Energy Requirements for Explosive Removal
by the APE 1300 Hot Water Washout and Recovery System

For the 155 mm M549 projectile:

Steam: (ref 16)*

$$\frac{1701 \text{ kg steam}}{\text{hour}} \times \frac{1 \text{ hour}}{426 \text{ kg Comp B}} \times \frac{7.26 \text{ kg Comp B}}{\text{projectile}} \times \frac{2.326 \times 10^6 \text{J}}{\text{kg steam}} = 67.4 \times 10^6 \text{J}$$

$$\left(\frac{3750 \text{ lbs steam}}{\text{hour}} \times \frac{1 \text{ hour}}{940 \text{ lbs Comp B}} \times \frac{16 \text{ lbs Comp B}}{\text{projectile}} \times \frac{1000 \text{ BTU}}{\text{lb steam}} = 63.8 \times 10^3 \text{ BTU}\right)$$

Electricity: (ref 16)

$$\frac{450 \times 10^6 \text{J}}{\text{hour}} \times \frac{1 \text{ hour}}{426 \text{ kg Comp B}} \times \frac{7.26 \text{ kg Comp B}}{\text{projectile}} = 7.7 \times 10^6 \text{J}$$

$$\left(\frac{125 \text{ kWh}}{\text{hour}} \times \frac{1 \text{ hour}}{940 \text{ lbs Comp B}} \times \frac{16 \text{ lbs Comp B}}{\text{projectile}} = 2.13 \text{ kWh}\right)$$

For the 8-inch XM650 projectile:

Steam:

$$\frac{1701 \text{ kg steam}}{\text{hour}} \times \frac{1 \text{ hour}}{426 \text{ kg Comp B}} \times \frac{11.8 \text{ kg Comp B}}{\text{projectile}} \times \frac{2.326 \times 10^6 \text{J}}{\text{lb steam}} = 109.6 \times 10^6 \text{J}$$

$$\left(\frac{3750 \text{ lbs steam}}{\text{hour}} \times \frac{1 \text{ hour}}{940 \text{ lbs Comp B}} \times \frac{26 \text{ lbs Comp B}}{\text{projectile}} \times \frac{1000 \text{ BTU}}{\text{lb steam}} = 103.7 \times 10^3 \text{ BTU}\right)$$

Electricity:

$$\frac{450 \times 10^6 \text{J}}{\text{hour}} \times \frac{1 \text{ hour}}{426 \text{ kg Comp B}} \times \frac{11.8 \text{ kg Comp B}}{\text{projectile}} = 12.5 \times 10^6 \text{J}$$

$$\left(\frac{125 \text{ kWh}}{\text{hour}} \times \frac{1 \text{ hour}}{940 \text{ lbs Comp B}} \times \frac{26 \text{ lbs Comp B}}{\text{projectile}} = 3.46 \text{ kWh}\right)$$

*References are located in the body of the report.

Energy Requirements for Explosive Removal.
by the Melt and Rinse Method

For the 155 mm M549 projectile:

Steam:

1) To melt: (ref 17)

$$\frac{18.1 \text{ kg steam}}{\text{projectile}} \times \frac{2.326 \times 10^6 \text{J}}{\text{kg steam}} = 42.2 \times 10^6 \text{J}$$

$$\left(\frac{40 \text{ lbs steam}}{\text{projectile}} \times \frac{1000 \text{ BTU}}{\text{lb steam}} = 40.0 \times 10^3 \frac{\text{BTU}}{\text{projectile}}\right)$$

2) To rinse: (ref 18)

$$\frac{75.3 \text{ kg } H_2O}{\text{projectile}} \times \frac{4.187 \times 10^3 \text{J}}{\text{kg } ^{\circ}\text{K}} \times 83^{\circ}\text{K} = 26.3 \times 10^6 \text{J}$$

$$\left[\left(\frac{10 \text{ gal } H_2O}{\text{min}} \times \frac{2 \text{ min}}{\text{proj}} \times \frac{8.3 \text{ lbs}}{\text{gal } H_2O}\right) \times \frac{1 \text{ BTU}}{\text{lb } ^{\circ}\text{F}} \times (200^{\circ}\text{F} - 50^{\circ}\text{F}) = 24.9 \times 10^3 \text{ BTU}\right)\right]$$

For the 8-inch XM650 projectile:

Steam:

1) To melt: assume steam requirement is proportional to mass of explosive

$$\frac{18.1 \text{ kg steam}}{\text{projectile}} \times \frac{11.8 \text{ kg Comp B}}{7.26 \text{ kg Comp B}} \times \frac{2.326 \times 10^6 \text{J}}{\text{kg steam}} = 68.4 \times 10^6 \text{J}$$

$$\left(\frac{40 \text{ lbs steam}}{\text{projectile}} \times \frac{26 \text{ lbs Comp B}}{16 \text{ lbs Comp B}} \times \frac{1000 \text{ BTU}}{1 \text{ lb steam}} = 65.0 \times 10^3 \text{ BTU}\right)$$

2) To rinse: assume a 3 minute rinse

$$\frac{113 \text{ kg } H_2O}{\text{projectile}} \times \frac{4.187 \times 10^3 \text{J}}{\text{kg } ^{\circ}\text{K}} \times 83^{\circ}\text{K} = 39.3 \times 10^6 \text{J}$$

$$\left[\left(\frac{10 \text{ gal } H_2O}{\text{min}} \times \frac{3 \text{ min}}{\text{proj}} \times \frac{8.3 \text{ lb}}{\text{gal } H_2O}\right) \times \frac{1 \text{ BTU}}{\text{lb } ^{\circ}\text{F}} \times (200^{\circ}\text{F} - 50^{\circ}\text{F}) = 37.4 \times 10^3 \text{ BTU}\right)\right]$$

Energy Requirements for Explosive Removal
by the High Pressure Washout Method with Explosive Drying

For the 155 mm M549 projectile:

Electricity: (ref 4)

$$P = k\,p\,Q = 1 \times 68.9 \text{ MPa} \times 1.39 \frac{\text{L}}{\text{s}} = 96 \text{ kW}$$

$$(P = 5.834 \times 10^{-4} \times 10{,}000 \text{ psi} \times 22 \text{ gpm} = 128 \text{ HP})$$

$$96 \text{ kW} \times \frac{2.43 \text{ min}}{\text{projectile}} \times \frac{1 \text{ min}}{60 \text{ min}} \times \frac{3.6 \times 10^6 \text{J}}{\text{kWh}} = 14.0 \times 10^6 \text{J}$$

$$\left(128 \text{ HP} \times \frac{1 \text{ kW}}{1.341 \text{ HP}} \times \frac{2.43 \text{ min}}{\text{projectile}} \times \frac{1 \text{ hour}}{60 \text{ min}} = 3.87 \text{ kWh}\right)$$

Steam: to dry the explosive prior to sale; assume 1 kg of steam is required to dry 1 kg of Comp B

$$\frac{1 \text{ kg steam}}{1 \text{ kg Comp B}} \times \frac{7.26 \text{ kg Comp B}}{\text{projectile}} \times \frac{2.326 \times 10^6 \text{J}}{\text{kg steam}} = 16.9 \times 10^6 \text{J}$$

$$\left(\frac{1 \text{ lb steam}}{1 \text{ lb Comp B}} \times \frac{16 \text{ lbs Comp B}}{\text{projectile}} \times \frac{1000 \text{ BTU}}{1 \text{ lb steam}} = 16.0 \times 10^3 \text{ BTU}\right)$$

For the 8-inch XM650 projectile:

Electricity: assume same rate of explosive removal so that cutting time is proportional to the mass of explosive to be removed, i.e.,

$$\frac{2.43 \text{ min}}{\text{proj}} \times \frac{11.8 \text{ kg Comp B}}{7.26 \text{ kg Comp B}} = 3.95 \text{ min}$$

$$96 \text{ kW} \times \frac{2.43 \text{ min}}{\text{projectile}} \times \frac{11.8 \text{ kg Comp B}}{7.26 \text{ kg Comp B}} \times \frac{1 \text{ hour}}{60 \text{ min}} \times \frac{3.6 \times 10^6 \text{J}}{\text{kWh}} = 22.7 \times 10^6 \text{J}$$

$$\left(128 \text{ HP} \times \frac{1 \text{ kW}}{1.341 \text{ HP}} \times \frac{2.43 \text{ min}}{\text{projectile}} \times \frac{26 \text{ lbs Comp B}}{16 \text{ lbs Comp B}} \times \frac{1 \text{ hour}}{60 \text{ min}} = 6.28 \text{ kWh}\right)$$

Steam:

$$\frac{1 \text{ kg steam}}{1 \text{ kg Comp B}} \times \frac{11.8 \text{ kg Comp B}}{\text{projectile}} \times \frac{2.326 \times 10^6 \text{J}}{\text{kg steam}} = 27.4 \times 10^6 \text{J}$$

$$\left(\frac{1 \text{ lb steam}}{1 \text{ lb Comp B}} \times \frac{26 \text{ lbs Comp B}}{\text{projectile}} \times \frac{1000 \text{ BTU}}{1 \text{ lb steam}} = 26.0 \times 10^3 \text{ BTU}\right)$$

Energy Requirements for Explosive Removal
by the CAVIJET Cavitating Jet Method with Explosive Drying

For the 155mm M549 projectile:

Electricity: a) use cleaning rate factor of 3/4 relative to high pressure washout, as derived in the text to estimate the time required to clean the projectile, i.e., (3/4) x (2.43 min) = 1.82 min

b) using a three-nozzle Cavijet cleaning head, with each nozzle having a 3.2 min (0.125 in) orifice diameter will require 3.4 $\frac{L}{s}$ (54 $\underline{gal}$) at 27.6 MPa (4,000 psi)

$$P = kpQ = 1 \times 27.4 \text{ MPa} \times 3.4 \frac{L}{s} = 94 \text{ kW}$$

$$(P = 5.834 \times 10^{-4} \times 4000 \text{ psi} \times 54 \text{ gpm} = 126 \text{ HP})$$

$$94 \text{ kW} \times \frac{1.82 \text{ min}}{\text{projectile}} \times \frac{1 \text{ hour}}{60 \text{ min}} \times \frac{3.6 \times 10^6 \text{J}}{\text{kWh}} = 10.3 \times 10^6 \text{J}$$

$$(126 \text{ HP} \times \frac{1 \text{ kW}}{1.341 \text{ HP}} \times \frac{1.82 \text{ min}}{\text{projectile}} \times \frac{1 \text{ hour}}{60 \text{ min}} = 2.85 \text{ kWh})$$

Steam: to dry the explosive prior to sale, assume 1 kg of steam is required to dry 1 kg of Comp B

$$\frac{1 \text{ kg steam}}{1 \text{ kg Comp B}} \times \frac{7.26 \text{ kg Comp B}}{\text{projectile}} \times \frac{2.326 \times 10^6 \text{J}}{\text{kg steam}} = 16.9 \times 10^6 \text{J}$$

$$(\frac{1 \text{ lb steam}}{1 \text{ lb Comp B}} \times \frac{16 \text{ lb Comp B}}{\text{projectile}} \times \frac{1000 \text{ BTU}}{1 \text{ lb steam}} = 16.0 \times 10^3 \text{ BTU})$$

For the 8 inch XM650 projectile:

Electricity: similarly, use cleaning rate factor of 3/4 and assume that cutting time is proportional to the mass of explosive to be removed.

$$94 \text{ kW} \times \frac{2.43 \text{ min}}{\text{projectile}} \times \frac{11.8 \text{ kg Comp B}}{7.26 \text{ kg Comp B}} \times \frac{3}{4} \times \frac{1 \text{ hour}}{60 \text{ min}} \times \frac{3.6 \times 10^6 \text{J}}{\text{kWh}} = 16.7 \times 10^6 \text{J}$$

$$(126 \text{ HP} \times \frac{1 \text{ kW}}{1.341 \text{ HP}} \times \frac{2.43 \text{ min}}{\text{projectile}} \times \frac{11.8 \text{ kg Comp B}}{7.26 \text{ kg Comp B}} \times \frac{3}{4} \times \frac{1 \text{ hour}}{60 \text{ min}} = 4.64 \text{ kW})$$

Steam: $$\frac{1 \text{ kg steam}}{1 \text{ kg Comp B}} \times \frac{11.8 \text{ kg Comp B}}{\text{projectile}} \times \frac{2.326 \times 10^6 \text{J}}{\text{kg steam}} = 27.4 \times 10^6 \text{J}$$

$$(\frac{1 \text{ lb steam}}{1 \text{ lb Comp B}} \times \frac{26 \text{ lb Comp B}}{\text{projectile}} \times \frac{1000 \text{ BTU}}{1 \text{ lb steam}} = 26.0 \times 10^3 \text{ BTU})$$

Cost Estimates for Explosive Removal by the Hot Water Washout and Recovery System

For the 155mm M549 projectile:

Steam:

$$\frac{1701\text{ kg steam}}{\text{hour}} \times \frac{1\text{ hour}}{426\text{ kg Comp B}} \times \frac{7.26\text{ kg Comp B}}{\text{projectile}} \times \frac{\$4.50}{454\text{ kg steam}} = \$0.29$$

$$\left(\frac{3750\text{ lbs steam}}{\text{hour}} \times \frac{1\text{ hour}}{940\text{ lb Comp B}} \times \frac{16\text{ lb Comp B}}{\text{projectile}} \times \frac{\$4.50}{1000\text{ lbs steam}} = \$0.29\right)$$

Electricity:

$$\frac{125\text{ kWh}}{\text{hour}} \times \frac{1\text{ hour}}{426\text{ kg Comp B}} \times \frac{7.26\text{ kg Comp B}}{\text{projectile}} \times \frac{\$0.055}{\text{kWh}} = \$0.12$$

$$\left(\frac{125\text{ kWh}}{\text{hour}} \times \frac{1\text{ hour}}{940\text{ lb Comp B}} \times \frac{16\text{ lb Comp B}}{\text{projectile}} \times \frac{\$0.055}{\text{kWh}} = \$0.12\right)$$

Water and Water Treatment: water is recirculated during operation; system is drained and replenished weekly

$$\frac{73{,}675\text{ L }H_2O}{\text{week}} \times \frac{1\text{ week}}{4000\text{ proj processed}} \times \frac{\$4.50}{3785\quad H_2O} = \$0.02$$

$$\left(\frac{19{,}463\text{ gal }H_2O}{\text{week}} \times \frac{1\text{ week}}{4000\text{ proj processed}} \times \frac{\$4.50}{1000\text{ gal }H_2O} = \$0.02\right)$$

Labor: (ref 19)

$$\frac{11\text{ men} \times 8\text{ hours}}{400\text{ projectiles}} \times \frac{\$20}{\text{man-hour}} = \$4.40$$

For the 8 inch XM650 projectile:

Steam:

$$\frac{1701\text{ kg steam}}{\text{hour}} \times \frac{1\text{ hour}}{426\text{ kg Comp B}} \times \frac{11.8\text{ kg Comp B}}{\text{projectile}} \times \frac{\$4.50}{454\text{ kg steam}} = \$0.47$$

$$\left(\frac{3750\text{ lbs steam}}{\text{hour}} \times \frac{1\text{ hour}}{426\text{ kg Comp B}} \times \frac{26\text{ lb Comp B}}{\text{projectile}} \times \frac{\$4.50}{1000\text{ lb steam}} = \$0.47\right)$$

Electricity:

$$\frac{125\text{ kWh}}{} \times \frac{1\text{ hour}}{426\text{ kg Comp B}} \times \frac{11.8\text{ kg Comp B}}{\text{projectile}} \times \frac{\$0.055}{\text{kWh}} = \$0.19$$

$$\left(\frac{125\text{ kWh}}{\text{hour}} \times \frac{1\text{ hour}}{940\text{ lb Comp B}} \times \frac{26\text{ lb Comp B}}{\text{projectile}} \times \frac{\$0.055}{\text{kWh}} = \$0.19\right)$$

Water and Water Treatment:

$$\frac{73{,}675\text{ L }H_2O}{\text{week}} \times \frac{1\text{ week}}{4000\text{ proj} \times \frac{7.26\text{ kg}}{11.8\text{ kg}}} \times \frac{\$4.50}{3785\text{ L }H_2O} = \$0.04$$

$$\left(\frac{19{,}463\text{ gal }H_2O}{\text{week}} \times \frac{1\text{ week}}{4000\text{ proj} \times \frac{16\text{ lb}}{26\text{ lb}}} \times \frac{\$4.50}{1000\text{ gal }H_2O} = \$0.04\right)$$

Labor:

$$\frac{11\text{ men} \times 8\text{ hours}}{400\text{ projectile}} \times \frac{11.8\text{ kg Comp B}}{7.26\text{ kg Comp B}} \times \frac{\$20}{\text{man-hour}} = \$7.15$$

$$\left(\frac{11\text{ men} \times 8\text{ hours}}{400\text{ projectile}} \times \frac{26\text{ lb Comp B}}{16\text{ lb Comp B}} \times \frac{\$20}{\text{man-hour}} = \$7.15\right)$$

Cost Estimates for Explosive Removal by the Melt and Rinse Method

For the 155mm M549 projectile:

Steam:

$$18.1 \text{ kg steam to melt} + 11.3 \text{ kg steam to heat rinse water} = 29.4 \frac{\text{kg steam}}{\text{projectile}}$$

$$\left(40 \text{ lbs steam to melt} + 24.9 \text{ lbs steam to heat rinse water} = 64.9 \frac{\text{lbs steam}}{\text{projectile}}\right)$$

$$29.4 \frac{\text{kg steam}}{\text{projectile}} \times \frac{\$4.50}{454 \text{ kg steam}} = \$0.29$$

$$\left(64.9 \frac{\text{lb steam}}{\text{projectile}} \times \frac{\$4.50}{1000 \text{ lb steam}} = \$0.29\right)$$

Water and Water Treatment:

$$0.631 \frac{\text{L}}{\text{s}} \times \frac{120 \text{ s}}{\text{proj}} \times \frac{\$4.50}{3785 \text{ L}} = \$0.09$$

$$\left(10 \frac{\text{gal}}{\text{min}} \times \frac{2 \text{ min}}{\text{proj}} \times \frac{\$4.50}{1000 \text{ gal}} = \$0.09\right)$$

Labor: (ref 20)

$$\frac{6 \text{ men} \times 8 \text{ hours}}{253 \text{ projectile}} \times \frac{\$20}{\text{man-hour}} = \$3.79$$

For the 8 inch XM650 projectile:

Steam:

$$29.4 \text{ kg steam to melt} + 17.0 \text{ kg steam to heat rinse water} = 46.4 \frac{\text{kg steam}}{\text{projectile}}$$

$$\left(65.0 \text{ lb steam to melt} + 37.4 \text{ lb steam to heat rinse water} = 102.4 \frac{\text{lb steam}}{\text{projectile}}\right)$$

$$46.4 \frac{\text{kg steam}}{\text{projectile}} \times \frac{\$4.50}{454 \text{ kg steam}} = \$0.46$$

$$\left(102.4 \frac{\text{lb steam}}{\text{projectile}} \times \frac{\$4.50}{1000 \text{ lb steam}} = \$0.46\right)$$

Water and Water Treatment:

$$0.631 \frac{\text{L}}{\text{s}} \times \frac{180 \text{ s}}{\text{proj}} \times \frac{\$4.50}{3785 \text{ L}} = \$0.14$$

$$\left(10 \frac{\text{gal}}{\text{min}} \times \frac{3 \text{ min}}{\text{proj}} \times \frac{\$4.50}{1000 \text{ gal}} = \$0.14\right)$$

Labor:

$$\frac{6 \text{ men} \times 8 \text{ hours}}{253 \text{ projectile}} \times \frac{11.8 \text{ kg Comp B}}{7.26 \text{ kg Comp B}} \times \frac{\$20}{\text{man-hour}} = \$6.17$$

$$\left(\frac{6 \text{ men} \times 8 \text{ hours}}{253 \text{ projectile}} \times \frac{26 \text{ lb Comp B}}{16 \text{ lb Comp B}} \times \frac{\$20}{\text{man-hour}} = \$6.17\right)$$

Cost Estimates for Explosive Removal
by the High Pressure Washout Method with Explosive Drying

For the 155mm M549 projectile:

Electricity: $\frac{3.87\ \text{kWh}}{\text{projectile}} \times \frac{0.055}{\text{kWh}} = \$0.21$

Steam: $7.26\ \frac{\text{kg steam}}{\text{projectile}} \times \frac{\$4.50}{454\ \text{kg steam}} = \$0.07$

$(16\ \frac{\text{lb steam}}{\text{projectile}} \times \frac{\$4.50}{1000\ \text{lb steam}} = \$0.07$

Water and Water Treatment: per ref 4, cutting time is 2.43 min, handling time is 0.33 min, flow rate through nozzle is 1.39 L/s (22 gpm)

$1.39\ \frac{\text{L}}{\text{s}} \times \frac{2.43\ \text{min}}{\text{proj}} \times \frac{60\ \text{s}}{1\ \text{min}} \times \frac{\$4.50}{3785\ \text{L}} = \$0.24$

$(22\ \frac{\text{gal}}{\text{min}} \times \frac{2.43\ \text{min}}{\text{proj}} \times \frac{\$4.50}{1000\ \text{gal}} = \$0.24)$

Labor: (refs 4 and 21)

$$\frac{3\ \text{men} \times 8\ \frac{\text{hour}}{\text{shift}}}{400\ \text{min} \times \frac{1\ \text{projectile}}{2.76\ \text{min}}} \times \frac{\$20}{\text{man-hour}} = \$3.31$$

Extra Maintenance: estimated based on literature and discussions; additional maintenance above routine maintenance due to the nature and complexity of the equipment.

$$\frac{8\ \text{hour downtime}}{\text{week}} \times \frac{1\ \text{week}}{144\ \frac{\text{proj}}{\text{shift}} \times \frac{5\ \text{days}}{\text{week}} \times 2\ \frac{\text{shifts}}{\text{day}}} \times 2\ \text{Men} \times \frac{\$20}{\text{man hour}} = \$0.22$$

Nozzle Replacement: (ref 21)

$\frac{\$8}{\text{nozzle}} \times \frac{1\ \text{nozzle}}{600\ \text{projectiles}} = \$0.01$

For the 8 inch XM650 projectile:

Electricity:

$6.28\ \frac{\text{kWh}}{\text{proj.}} \times \frac{\$0.055}{\text{kWh}} = \$0.35$

Steam:

$11.8\ \frac{\text{kg steam}}{\text{proj}} \times \frac{\$4.50}{454\ \text{kg steam}} = \$0.12$

$(26\ \frac{\text{lb steam}}{\text{prog}} \times \frac{\$4.50}{1000\ \text{lb steam}} = \$0.12)$

Water and Water Treatment: use cutting time = 3.95 min

$1.39\ \frac{\text{L}}{\text{s}} \times \frac{3.95\ \text{min}}{\text{proj}} \times \frac{60\ \text{s}}{\text{min}} \times \frac{\$4.50}{3785\text{L}} = \$0.39$

$(22\ \frac{\text{gal}}{\text{min}} \times \frac{3.95\ \text{min}}{\text{projectile}} \times \frac{\$4.50}{1000\ \text{gal}} = \$0.39)$

Labor: refs 4 and 21; assume handling time = 1.0 min, therefore total time per projectile = 3.95 min + 1.0 min = 4.95 min

$$\frac{3\text{ men} \times 8\ \frac{\text{hours}}{\text{shift}}}{400\ \frac{\text{min}}{\text{shift}} \times \frac{1\text{ proj}}{4.95\text{ min}}} \times \frac{\$20}{\text{man hour}} = \$5.94$$

Extra Maintenance: similarly as for the 155mm projectile

$$\frac{8\text{ hours downtime}}{\text{week}} \times \frac{1\text{ week}}{\frac{80.8\text{ proj}}{\text{shift}} \times \frac{5\text{ days}}{\text{week}} \times \frac{2\text{ shifts}}{\text{day}}} \times 2\text{ men} \times \frac{\$20}{\text{man hour}} = \$0.40$$

Nozzle Replacement: assume wear is proportional to mass of explosive removed

$$\frac{\$8}{\text{nozzle}} \times \frac{1\text{ nozzle}}{600\text{ proj} \times \frac{7.26\text{ kg Comp B}}{11.8\text{ kg Comp B}}} = \$0.02$$

Cost Estimates for Explosive Removal
by the CAVIJET Cavitating Jet Method with Explosive Drying

For the 155mm M549 projectile

Electricity:

$$\frac{2.85\ \text{kWh}}{\text{projectile}} \times \frac{\$0.055}{\text{kWh}} = \$0.16$$

Steam:

$$\frac{7.26\ \text{kg steam}}{\text{projectile}} \times \frac{\$4.50}{454\ \text{kg steam}} = \$0.07$$

Water and Water Treatment: as derived in the text, use cutting time = 1.82 min, handling time = 0.33 min; assume water recirculation; 3785L are drained and replaced daily (2 shifts)

$$\frac{3785\ \frac{\text{L}}{\text{day}}}{400\ \frac{\text{min}}{\text{shift}} \times \frac{1\ \text{proj}}{1.82\ \text{min}} \times \frac{2\ \text{shifts}}{\text{day}}} \times \frac{\$4.50}{3785\ \text{L}} = \$0.01$$

$$\frac{1000\ \frac{\text{gal}}{\text{day}}}{400\ \frac{\text{min}}{\text{shift}} \times \frac{1\ \text{proj}}{1.82\ \text{min}} \times \frac{2\ \text{shifts}}{\text{day}}} \times \frac{\$4.50}{1000\ \text{gal}} = \$0.01$$

Labor:

$$\frac{3\ \text{man} \times 8\ \frac{\text{hours}}{\text{shift}}}{400\ \frac{\text{min}}{\text{shift}} \times \frac{1\ \text{proj}}{2.15\ \text{min}}} \times \frac{\$20}{\text{man hour}} = \$2.58$$

Extra Maintenance: estimated; due to the nature and complexity of the equipment

$$\frac{4\ \text{hours downtime}}{\text{week}} \times \frac{1\ \text{week}}{400\ \frac{\text{min}}{\text{shift}} \times \frac{1\ \text{proj}}{2.15\ \text{min}} \times \frac{5\ \text{days}}{\text{week}} \times \frac{2\ \text{shifts}}{\text{day}}} \times 2\ \text{men} \times \frac{\$20}{\text{manhour}} = \$0.09$$

Nozzle Replacement: estimated

$$\frac{\$500}{\text{cutting head}} \times \frac{2\ \text{cutting heads}}{\text{year}} \times \frac{1\ \text{year}}{39{,}900\ \text{proj}} = \$0.03$$

For the 8 inch XM650 projectile

Electricity:

$$\frac{4.64\ \text{kWh}}{\text{projectile}} \times \frac{\$0.055}{\text{kWh}} = \$0.26$$

Steam:

$$\frac{11.8\ \text{kg steam}}{\text{projectile}} \times \frac{\$4.50}{454\ \text{kg steam}} = \$0.12$$

Water and Water Treatment: as derived in the text, use cutting time = $2.43 \times \frac{11.8}{7.26} \times \frac{3}{4} =$ 2.96 min, handling time = 1.0 min; assume water recirculation; 3785 are drained and replaced daily (2 shifts)

$$\frac{3785 \frac{L}{day}}{400 \frac{min}{shift} \times \frac{1\ proj}{2.96\ min} \times \frac{2\ shifts}{day}} \times \frac{\$4.50}{3785\ L} = \$0.02$$

$$\left(\frac{1000 \frac{gal}{day}}{400 \frac{min}{shift} \times \frac{1\ proj}{2.96\ min} \times \frac{2\ shifts}{day}} \times \frac{}{1000\ gal} = \$0.02\right)$$

Labor:

$$\frac{3\ men \times 8 \frac{hours}{shift}}{400 \frac{min}{shift} \times \frac{1\ proj}{3.96\ min}} \times \frac{\$20}{man\ hour} = \$4.75$$

Extra Maintenance: similarly as for the 155mm projectile

$$\frac{4\ hours\ downtime}{week} \times \frac{1\ week}{400 \frac{min}{shift} \times \frac{1\ proj}{3.96\ min} \times \frac{5\ days}{week} \times \frac{2\ shifts}{day}} \times 2\ men \times \frac{\$20}{man\ hour} = \$0.16$$

Nozzle Replacement: estimated; assume wear is proportional to mass of explosive removed

$$\frac{\$500}{cutting\ head} \times \frac{2\ cutting\ heads}{39{,}900\ 155\ mm\ proj} \times \frac{11.8\ kg\ Comp\ B}{7.26\ kg\ Comp\ B} = \$.04$$

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